Water Temperature, River Discharge, and Adult Chinook Salmon Migration Observations in the Cowichan Watershed, 1988-2014

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WATER TEMPERATURE, RIVER DISCHARGE, AND ADULT CHINOOK SALMON MIGRATION OBSERVATIONS IN THE COWICHAN WATERSHED, 1988-2014

by

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ABSTRACT

Damborg, J.G., Stiff, H.W., Hyatt, K.D., Brown, G., and Baillie, S. 2015. Water temperature, river discharge, and adult Chinook migration observations in the Cowichan Watershed, 1988-2014. Can. Manuscr. Rep. Fish. Aquat. Sci. 3028: vi + 92 p.

Historical daily mean air and water temperatures, stream discharge and adult Chinook salmon upstream migration data were assembled for the Cowichan River, British Columbia. Long-term air temperature time-series were statistically related to intermittent water temperature time-series to hind-cast daily water temperatures for the Lower Cowichan River from 1913-2014. Statistical relationships between the long-term WATER SURVEY OF CANADA (WSC) hydrometric station on the Upper Cowichan River (1913-2012), and the Lower Cowichan WSC station, were used to extend the discharge time-series for the Lower Cowichan site. Peak-over-threshold analyses were then applied to reconstructed time-series data to review trends.

Daily mean water temperature and discharge were correlated with adult Chinook migration rates at the Lower Cowichan River DFO counting fence between 1988 and 2014. Approximately 60% of all migration dates were characterized by river flows of < 10 cms. Daily migration rates at these flow levels were, however, low: <1.6% of annual counts. Comparatively high average migration rates (3-5% per day) were found at water temperatures between 13-15°C and flows of >10 cms, with peak migration rates occurring bi-modally at 30-36 cms following fall rain storm events, and, to a lesser extent, at 16-22 cms, corresponding to controlled "pulse" flow releases from the CATALYST PAPER CORPORATION weir at Cowichan lake. When partitioned by flow type (natural vs pulsed), a significant improvement in mean daily migration rate was apparent under pulsed flow conditions at low- to mid-level flow categories.

The frequency of dates where water temperatures exceeded 17°C during migration (September-November) fluctuated around 10-12 days per year between the 1960s and 1980s but increased to 15-19 in the past two decades, concurrent with an apparent increase in the average duration of periods continuously exceeding 17°C from ~18 days to ~25 days, though the trend is not statistically significant. The mean number and duration of annual "low flow" dates (flows <5 cms) were significantly reduced after the flow control weir was installed at the Cowichan Lake outlet in the late 1950s, but have been rising since the 1980s, primarily in late summer before significant Chinook migration occurs, but increasingly extending into September and October during peak migration. However, trends in recent years remain insignificant.

RÉSUMÉ

Damborg, J.G., Stiff, H.W., Hyatt, K.D., Brown, G., et Baillie, S. 2015. Observations sur la température de l'eau, le débit fluvial et la migration du saumon quinnat dans le bassin versant de la rivière Cowichan, de 1988 à 2014. Rapp. man. can. sci. halieut. aquat. 3028: 3028: vi + 92 p.

On a colligé les données historiques sur les moyennes quotidiennes de la température de l'air et de l'eau, du débit du cours d'eau et de la montaison des saumons quinnat adultes dans la rivière Cowichan, en Colombie-Britannique. La série chronologique à long terme de la température de l'air a été rapprochée statistiquement de la série chronologique intermittente de la température de l'eau afin de prévoir *a posteriori* les températures de l'eau quotidiennes dans le cours inférieur de la Cowichan de 1913 à 2012. Les relations statistiques de la station hydrométrique de la Division des relevés hydrologiques du Canada située dans le cours supérieur de la Cowichan (1913-2012) et celles de la station située dans le cours inférieur de la Cowichan ont été utilisées pour prolonger la série chronologique sur l'écoulement du site du cours inférieur de la Cowichan. Des analyses des dépassements des seuils ont été appliquées aux séries chronologiques reconstituées pour examiner les tendances.

Les valeurs médianes de la température et du débit quotidiens de l'eau ont été mises en corrélation avec les taux de migration du saumon quinnat à la barrière de dénombrement de Pêches et Océans Canada dans le cours inférieur de la Cowichan entre 1988 et 2012. Environ 60 % de toutes les dates de migration étaient caractérisées par un débit de moins de 10 cm/s. Les taux de migrations quotidiens à ces niveaux de débit étaient cependant faibles : moins de 1,3 % des échappées annuelles. Toutefois, des températures de l'eau plus basses (moins de 17 °C) ne suffisaient généralement pas pour qu'ait lieu une importante migration. Des taux de migration élevés en comparaison (plus de 3 % par jour) ont été observés lorsque la température de l'eau variait entre 13 et 15 °C et que le débit atteignait plus de 10 cm/s, avec des pics du taux de migration à un débit de 18 à 20 cm/s, ce qui correspond au débit intermittent régulé au barrage de la Catalyst Paper Corporation, au lac Cowichan, ou au débit non régulé d'environ 30 cm/s suivant les tempêtes automnales. L'analyse pondérée de la fréquence des taux de migration du saumon quinnat pour toutes les combinaisons de débits et de températures reflète un « environnement de migration de prédilection » dans le cours inférieur de la Cowichan à un débit variant entre 12 et 25 cm/s et à une température de l'eau se situant entre 12 et 17 °C.

La fréquence des jours où la température de l'eau dépassait 17 °C pendant la migration (de septembre à novembre) était d'environ 10à 12 jours par an des années 1960 aux années 1980, mais elle a augmenté à 15 à 19 jours au cours des 20 dernières années, parallèlement à une hausse de la durée moyenne des périodes pendant lesquelles la température de l'eau dépassait les 17 °C, d'environ 18 à 25 jours. La moyenne du nombre de jours et de la durée annuelle des périodes de « faible débit » (débit de moins de 5 cm/s) a considérablement diminué après l'installation d'une structure de régulation du débit au dégorgeoir du lac Cowichan

vers la fin des années 1950, mais elle a augmenté depuis les années 1980, surtout à la fin de l'été, avant l'importante migration du saumon quinnat mais se étend de plus en plus en Septembre et Octobre lors de la migration de pointe. Tendances au cours des dernières années restent insignifiants, cependant.

INTRODUCTION

Temperature effects on migrating adult Chinook salmon (*Oncorhynchus tshawytscha*) have been well documented in many river systems in the Pacific Northwest. High water temperatures affect Chinook migration rate (Goniea et al. 2006; Salinger and Anderson 2006), cause timing delays (Strange 2010; Salinger and Anderson 2006; Keefer et al. 2008), and alter spatial distribution (Torgersen et al. 1999). Lethal temperatures range between 21 and 24°C (McCullough 1999; Richter and Kolmes 2005; Poole 2001). Increased water temperature may also result in secondary stressors such as more virulent diseases, resulting in pre-spawn mortality (McCullough 1999; Richter and Kolmes 2005; Holt et al. 1975). Thermal stress has also been found to reduce gamete viability, fertilization rates and decrease egg-to-fry survival rates (McCullough 1999).

The range of Chinook salmon in North America extends from Western Alaska as far south as Central California (Healey 1991). This range is thought to be influenced foremost by the thermal environment (McCullough et al. 2001). Tolerance for high water temperatures is generally greater for fish in the southern region of the species' range, as they have apparently adapted to the warmer climate, and consequently warmer water temperatures (Farrell 2009). Studies conducted on the Columbia River, Oregon, suggest "stop migration events" occur at approximately 20-21°C (McCullough 1999; Goniea et al. 2006; Strange 2010) and slower migration, pre-spawn mortality, and/or stress effects occur at temperatures above 16-17°C (McCullough 1999). Stream discharge is also known to impact in-stream migration of adult salmonids; however, the effects may differ between streams due to unique physical characteristics of a given stream. In some instances, low flow may be preferred for migration (Keefer et al. 2008); in other systems, low flow may present physical obstacles to migration (Torgersen et al. 1999).

It is anticipated that with increasing temperatures and reduced summer rainfall as a result of climate change (Mote and Salathé 2009), that wild salmon populations in the Pacific Northwest and coastal British Columbia will become increasingly stressed to their physical and physiological limits, potentially leading to general abundance declines and, in severe cases, extinctions (Richter and Kolmes 2005). The current report is one of a series intended to consolidate and document historic observations on key life history events and associated environmental variables for relatively data-rich Sockeye and Chinook salmon populations distributed throughout their range in Canada's Pacific region. Although there are many potential uses for these data, the focus of our current work is to develop life-stage-specific models that identify potential associations between salmon production variations and climate variation effects in freshwater and marine ecosystems throughout the eastern rim of the north Pacific.

The Cowichan was selected for initial investigations given the fact it is a 'data rich' watershed, in that data is readily available and considered reliable (i.e., significant efforts have been spent over the last 30 years enumerating migrating adult Chinook salmon, monitoring juvenile outmigration, and collecting temperature and flow data).

Results from this analysis can then be potentially used for predictive purposes in neighboring 'data poor' systems where Chinook stocks may also be at risk.

STUDY AREA

The Cowichan River flows from its outlet at Cowichan Lake 47 km through the Cowichan Valley in a generally easterly direction to its estuary at Cowichan Bay, where it meets the lower Strait of Georgia (Figure 1, Figure 2). The Cowichan has a total watershed area of 1,227 km^2, a mean annual discharge (MAD) of 55 cms and is considered to be a highly productive fish-producing stream (Lill 2002). The upper basin, including Cowichan Lake, lies at the foot of the Insular Mountains and receives approximately 2,800 mm of precipitation annually, while the lower catchment, downstream of the lake to the estuary, receives an average 1,100 mm each year (Westland 2007).

Cowichan Lake is the largest lake on southern Vancouver Island, with a surface area of 6,214 ha. It lies at an elevation of 164 m above sea level. The Cowichan is a pluvial watershed with the majority of annual precipitation falling as rain. In winter, snow accounts for proportionally more of the precipitation in the mountainous, western section of the basin. Highest flows generally occur in fall/winter, triggered by significant rainfall or rain-on-snow events. The low flow period is typically mid-July through late September. To help facilitate anadromous fish migration to the upper watershed, a fishway was constructed at Skutz Falls in 1931 and then modified in 1937. Since its construction, fish generally have unimpeded access to the upper river at most flow levels, where the highest value spawning habitat exists and is used extensively by fall Chinook (M. Sheng, DFO Biologist, pers. comm.).

The lake basin has been heavily developed over the past 100 years, initially for forest harvesting and, more recently, residential development. Historically, the foreshore of Cowichan Lake had as many as six log dump/sort locations and two lumber mills. There are significant water withdrawals from the mainstem Cowichan, the largest being the extraction of up to 1.8 cms by CATALYST PAPER CORP. for use at the Crofton paper mill. To mitigate industrial water extraction the mill was required under water licence to build a one-meter low head weir at the outlet of Cowichan Lake in 1956 to provide seasonal water storage (61.3M m^3) to augment naturally low summer river flows (Hop Wo, Nagtegaal, and Carter 2005)[1]. Summer base flows in the Cowichan River are generally maintained near 7 cms from July to October, which typically equates to 4-5 cms at the WSC hydrometric station in the lower river near Duncan, depending on CATALYST pump house withdrawals, domestic and agricultural demands[2], and natural channel losses (i.e., seepage to groundwater).

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[1] Seasonally stored water in Cowichan Lake is released at the weir into Cowichan River and withdrawn downstream near the City of Duncan ten kilometres upstream of the estuary, and pumped by pipeline to the Crofton mill.

[2] Underground aquifers supply the domestic water needs for the City of Duncan and other communities in the Cowichan Basin, including dilution of treated sewage discharges (Cowichan Valley Regional District Water Management http://www.cvrd.bc.ca/).

The lake and its tributary basins support a diverse community of fish species, both native and introduced, including Coho, Chinook, Chum and Kokanee salmon, Winter Steelhead Trout, German Brown, Coastal Cutthroat and Rainbow trout, Dolly Varden and Brook char, three species of lamprey, Three-spine stickleback and two sculpin species. Small lakes in the Lower Cowichan watershed also support Smallmouth Bass and Brown Catfish[3].

The Cowichan's fall Chinook population is one of the largest in the Georgia Basin, with historical spawner abundance ranging from 5,000 to 10,000 annually (Nagtegaal and Carter 2000). More recently, stocks have dwindled to an average of 2,800 adults and 1,150 jacks over the last 10 years, including an all-time low of 785 adults and 281 jacks in 2009. Reasons for sharp declines are not fully understood but may be attributed in some years to extremely low river water levels possibly contributing to adult spawner mortality (Nagtegaal, Carter, and Hop Wo 2006; Nelitz et al. 2007), as well as a general decline in marine survival since at least 1991 (Burt et al. 2002; Riddell, Nagtegaal, and Chen 2000).

The Cowichan River hatchery was established in 1978 and has released as many as 2.5M fall Chinook fry annually (Nagtegaal and Carter 2000), with an egg take target of 3,000,000. Cowichan Chinook remain an important resource for commercial, sport and First Nation fisheries which are valued at up to $6.2 M annually (McMullan 2006). Cowichan Chinook are also an index stock under the Canada-US Pacific Salmon Treaty, whose abundance trends are used to help guide broader management of the species in southern BC and American waters (Nelitz et al. 2007).

METHODS

DATA SOURCES AND ANALYSIS

Chinook Migration Data

Daily large adult Chinook escapement estimates (1986-2012, 2014[4]) were provided by FISHERIES AND OCEANS CANADA.[5] The Cowichan River adult enumeration fence is located at the old City of Duncan pumphouse (1986-2007) and was subsequently relocated immediately downstream of Allenby Road bridge (2008-present), approximately ten kilometres upstream of the estuary. The fence that was used from 1988 to 2007 could only monitor salmon migration below water levels of approximately 22 cms. Fence improvements in 2008 enabled reliable migrant counts at flows of 22-35 cms.

The fence is usually operated from early September until the end of October with observers present 24 hours a day. The enumeration fence is a floating weir design, spanning the river, guiding fish through an illuminated trap-box, where they are

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[3] Fish database (FISS) 2013.

[4] Daily counts in 2013 were omitted from analyses as the weir was overtopped by early flood waters on Sep 30th.

[5] Maintained by DFO South Coast personnel (S. Baillie, DFO; unpub. data).

counted by observers and recorded on digital video.[6]

Migration data collected in-season are finalized post-season by DFO personnel (Burt and Robert 2002):

> In some years, the fence count is augmented with a mark/recapture program involving the tagging of fish at the fence and subsequent recovery of carcasses on the spawning grounds. In some years extrapolations have to be made for fish that migrate before and after the fence installation, or if the fence has to be removed during a flood event.

Migration data used for the purpose of this report may not be consistent with other published or non-published estimates reported for this system (i.e., total run size). Given the need for empirical data to characterize daily upstream migration patterns, only un-interpolated and un-extrapolated fish counts through the fence were utilized. Therefore, the reported total run/escapement will generally be higher for any given year, since that total may include brood stock removals for the hatchery, assisted transport of fish (trapping/trucking) around the fence site that were not tallied by date, as well as data extrapolation for trap/fence efficiencies. It should also be noted that for some years where stream flows rose sharply during the main migration period, many (if not all) fish may be missed during high water events. This is evident during years when migration rises very sharply and then appears to end with no 'tailing off' that one would expect for the end of the run.

Data issues identified in the Chinook migration data, and remedied in the import process prior to analysis, include:

1. Ensuring only raw Chinook counts were used, with no interpolation or extrapolation;
2. Deleting days of partial data (i.e., if the fence was overtopped by a high water event);
3. QC/QA for gross errors in count data.

To standardize the annual adult migration time-series for inter-year and inter-stock comparisons, daily percentages of Cowichan Chinook migrants were calculated relative to the total annual fence counts (i.e., excluding interpolations and other adjustments). Annual plots of daily and cumulative migration rate (% relative to the annual total escapement) were generated, overlaid with historical mean and maximum daily migration rate by Julian day-of-year, for inter-annual migration pattern comparisons.

Univariate statistical analyses were used to characterize the historical stock migration data [number of observations, location (mean, median, mode, etc.); scale (range, variance, extreme values and outliers), and shape (skewness, kurtosis)]. Median (50th percentile) and 75th quartile values of the historical datasets were calculated to establish low (0-75th percentile), medium (75-90th percentile) and high (90-100th percentile) categories for daily migration rate classification. Quartiles of the Julian dates of migration in the historical data were used to categorize daily migrant

[6] The adult counting weir and operations are described in detail by Hop Wo et al. 2005.

data into early (0-25th percentile), middle (25-50th percentile), and late (75-100th percentile) observations. Daily migration rate data may be transformed using the arcsin function to normalize the percentage data, where appropriate, for use in parametric analyses (Sokal and Rohlf 1969).

No date lags were required for the purposes of aligning daily Chinook migration timing with environmental variables along the freshwater migratory route, since environmental data sampling was coincident (within one day of fish travel time) with migration data counts.

Environmental Data

Physical data, including air temperature, precipitation and water temperature were assembled from existing electronic databases, published documents, unpublished reports and personal records from a variety of sources including government agencies (e.g., B.C. MINISTRY OF ENVIRONMENT, ENVIRONMENT CANADA, WATER SURVEY OF CANADA, and FISHERIES AND OCEANS CANADA), public utilities (B.C. HYDRO), industry (CATALYST PAPER CORPORATION), as well as private and non-governmental organizations.

Basic statistical analyses were required to document and describe the available data, as well as establish relationships between regional air and site-specific water temperature datasets, as well as inter-site relations for both water temperature and discharge to infill missing observations. STATISTICAL ANALYSIS SOFTWARE (SAS® Version 9.3) was used to for data analyses. The resulting datasets were stored in a relational MICROSOFT ACCESS® FRESHWATER ENVIRONMENTAL VARIABLES DATABASE and are available from DFO upon request.[7]

River Discharge

Total daily discharge (cms) data for the Cowichan watershed were obtained from the archives at the WATER SURVEY OF CANADA (WSC) website.[8] WSC stations utilized in this analysis include:

- *Cowichan River (Lower) near Duncan* (Station 08HA011, 48°46'22"N x 123°42'52"W, 1960-2012; supplemented with real-time data for 2013-2014); and
- *Cowichan River (Upper) near Lake Cowichan* (Station 08HA002, 48°49'34"N x 124°03'07"W, 1913-2011); for extending the Lower Cowichan River time-series prior to 1960 via statistical regression.

With the exception of the real-time data, these datasets undergo detailed quality-control analysis before posting to the WSC web site.

Since continuous daily discharge data for the *Lower Cowichan* station commenced in 1960, statistical relations were developed with *Upper Cowichan* data to reconstruct discharge for prior periods for historical trend analyses of flows in the Lower Cowichan. Regression models were employed to develop station-to-station

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[7] Contact Kim.Hyatt@dfo-mpo.gc.ca (Scientist, Salmon and Freshwater Ecosystems, PBS, DFO).
[8] ENVIRONMENT CANADA – WATER SURVEY OF CANADA website: http://www.wsc.ec.gc.ca/applications/H2O/HydromatD-eng.cfm.

discharge equations for the *Lower Cowichan*[9] as a function of same-day *Upper Cowichan River*[10] discharge, excluding experimental pulse flow dates (which introduce a temporal effect due to a 12-hour delay between upper and lower river flow levels (Hop Wo et al. 2005)). Regression models included the simple linear model ($Y = A + BX$); a nonlinear model ($Y = AX^B$); and, a curvilinear model ($Y = A + BX + cX^2$). Calibration data were partitioned from the datasets by selecting every 10th daily observation; this also served to reduce the error associated with parametric analyses of auto-correlated time-series. Validation data were based on all available data. The most appropriate model was selected based on goodness of fit tests, and correlation analysis was used to compare predicted discharge time-series with observed discharge, where available.

Air Temperature

ENVIRONMENT CANADA'S METEOROLOGICAL SERVICES group maintains an archive of climate, hydrographic and water quality data gathered from both active and inactive stations distributed throughout British Columbia and the Yukon. Station locations and of data descriptions can be found at the ENVIRONMENT CANADA (EC) climate data archive[11]. This web site was accessed to identify potential sites of air temperature data within the area of interest (Figure 2) for statistical analyses with water temperature data.

For the majority of Canadian climate stations, air temperature measurements are taken from self-registering, maximum and minimum thermometers that record the extremes of each parameter within a 24-hour period. Daily mean temperature, where provided, is defined as the average of the maximum and the minimum temperatures attained during the 24-hour period. These datasets undergo detailed quality-control analysis before posting to the web site.

Climate station 1017230 (*Shawnigan Lake*) was selected for climate data retrieval based on: (i) the quantity and quality of data available; (ii) proximity to the Cowichan watershed (<25 km) (Figure 2); and, (iii) the potential to routinely update data (i.e. *Shawnigan Lake* is an "active" climate station). In addition, Environment Canada has refined the air temperature and precipitation time-series for this station, as part of the ADJUSTED AND HOMOGENIZED CANADIAN CLIMATE DATA (AHCCD) group of climatological stations across Canada[12]. These data incorporate a number of adjustments applied to the original station data to address shifts due to changes in instruments and in observing procedures, thus optimizing their use in climate research including climate change studies (Vincent et al. 2012).

Homogenized and adjusted daily temperature data (daily maximum, minimum and mean) were obtained for *Shawnigan Lake* for the period April 1913 to December 2013; 2014 data from the unadjusted *Shawnigan Lake* station 1017230 were

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[9] *Lower Cowichan River* drainage area: 826 km^2 (WSC)
[10] *Upper Cowichan River* drainage area: 594 km^2 (WSC)
[11] ENVIRONMENT CANADA Climate Data: http://climate.weatheroffice.gc.ca/climateData/canada_e.html
[12] ADJUSTED AND HOMOGENIZED CANADIAN CLIMATE DATA (AHCCD) – See http://www.ec.gc.ca/dccha-ahccd/default.asp?lang=En&n=B1F8423A-1

appended to the time-series until adjusted data become available.[13]

SHAWNIGAN LAKE MULTI-DAY MEAN AIR TEMPERATURE INDEX

Reconstruction of an historic, long-term, freshwater thermal regime requires a set of daily mean air temperature records spanning multiple decades. The best predictive air-water relationships exist for associations between daily mean water and multi-day mean air temperature (Mohseni and Stefan 1999; Hyatt and Stockwell 2003; Webb and Nobilis 1997). Centered moving averages (i.e., mean temperatures from *Date – (n-1)/2* to *Date + (n-1)/2*, where *n* is the number of days) center the multi-day means such that peaks and troughs more accurately align with the flux in the original daily MAT time-series (Hyatt et al. 2015).

MAT indices calculated over extended periods ($1< n <10$) lead to improved correlations with water temperature data, which is key to developing good predictive models for air/water temperature relations. But MAT indices at larger *n*-values are also characterized by reduced day-to-day variability due to the centralizing effect of averaging, which reduces the power of the MAT index as a predictor for variation in water temperatures. Correlation analysis was used to identify the multi-day moving average air temperature index with the lowest *n*-value (for $n = 1, 3, 5, 7, 10$ days)[14] while retaining a high Pearson correlation coefficient with site daily mean water temperature. The multi-day *Shawnigan Lake* CMAT index with the lowest adjusted AKAIKE INFORMATION CRITERION (AICc) and the highest Pearson correlation coefficient for calibration data was used for subsequent air/water temperature regression relations.[15]

Univariate statistical analyses were used to characterize the selected air temperature index for the period of historical migration data, i.e., number of observations, location (mean, median, mode, etc.), scale (range, variance, extreme values and outliers), and shape (skewness, kurtosis). A threshold exceedance analysis, tallying the decadal mean monthly frequency of dates for which the multi-day air temperature index exceeded 20°C, was used to examine trends in high temperature events.[16]

Precipitation

The EC METEOROLOGICAL SERVICES web site was queried for total daily precipitation (mm) for the available years (1913-2014) for the *Shawnigan Lake* regional climate station specified above. Note that missing precipitation data were not interpolated or in-filled from other stations. Precipitation data are included in this compendium of physical data as they are generally correlated with discharge levels and in some cases, water temperature. They may also be useful for downscaling projected

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[13] AHCCD Licence Agreement: This work contains data licenced "as is" under the Government of Canada Open Data Licence Agreement. Such licencing does not constitute an endorsement by the Government of Canada of this product.

[14] $n = 1$ corresponds to the "observed" *Shawnigan Lake* mean daily air temperature time-series.

[15] Although the 10-d CMAT index was included in this assessment, and (usually) generated the maximum correlation, this index was ultimately discarded due to the undesired trade-off between high correlation versus the damping effect on daily air temperature variation, described above.

[16] Mote et al (2003) suggest a monthly average air temperature of 20°C to be a dependable upper threshold for identifying suitable salmon habitat.

changes in regional precipitation due to climate variation at the local level, as is available from most climate model outputs.

Water Temperature

Water temperature data were assembled for key sites along the migratory route of Cowichan Chinook, including the Lower Cowichan River at or near the Crofton CATALYST PAPER CORPORATION (CPC) pump-house, and the Upper Cowichan near Lake Cowichan (Figure 2). A variety of sources and data types (e.g., instantaneous measures from hand held thermometers, and sub-daily samples from automated thermographs) were assembled for these locations. Electronic records of thermograph readings were received as point temperatures at regular intervals across the 24-hour period, or as average temperatures of multiple samples across the interval. Sub-daily interval data ranged from half-hourly, to hourly, to measurements taken every 3, 4, 6, 8, or 12 hours. When multiple sources provided data for the same location and time period, the source covering the longest interval of time with the best temporal resolution was chosen for inclusion in this study. All datasets were stored in the Microsoft Access® FRESHWATER ENVIRONMENTAL VARIABLES DATABASE[17].

For the purposes of this study of factors affecting upstream migration, data from the Lower Cowichan River were of most interest. CPC data were selected for the reference water temperature dataset, as these data represented the most extensive time-series. Lower Cowichan water temperatures have been recorded hourly since 2000 at the site of the CATALYST pump-house (Figure 2) (source: CPC). Cowichan water temperature data were supplemented in 2004 and 2012 with hourly mean water temperatures obtained from data loggers installed in the lower and upper Cowichan River by DFO (2004; source: R. Ferguson, PBS, Nanaimo) and the B.C. CONSERVATION FOUNDATION (BCCF, Nanaimo). Overlapping Lower Cowichan datasets from DFO and BCCF sources were compared to the Catalyst data to determine statistical equivalence for possible infilling of missing data, using two-sample t-tests, assuming unequal variance.

Water temperature, data cleanup consisted of examining descriptive statistics and graphic output to identify anomalous data and outliers, in conjunction with a review of field notes regarding data logger installation and removal dates/times. All anomalous data were retained in the database but flagged for omission (i.e., OMIT field = YES) from data analyses.

Univariate statistical analyses were used to characterize the site-specific daily mean water temperature (MWT) time-series for the period of record [i.e., number of observations, location (mean, median, mode, etc.), scale (range, variance, extreme values and outliers), and shape (skewness, kurtosis)]. A subset of the selected daily MWT time-series was used with the selected mean air temperature (MAT) index to calibrate site-specific air-to-water temperature regression relations described below.

A threshold exceedance analysis, tallying the decadal mean monthly frequency of dates for which the reconstructed MWT temperature index exceeded 17°C, was

[17] MICROSOFT ACCESS® relational database, available from the authors.

used to examine site-specific trends in water temperature conditions during the adult migration period.

Air/Water Temperature Relationships

Variations in local air temperature, averaged over multiple days, are generally sufficient to explain as much as 80% of the seasonal variations in local daily mean water temperature (MWT), utilizing either linear or nonlinear regression models (Mohseni and Stefan 1999). Hyatt et al. (2015) describe the basic methodology used to estimate missing or historical daily MWTs based on statistical relations with the regional 7-day MAT index. The authors calibrated linear (Equation 1) and logistic (Equation 2) temperature relations using a subset of the site daily MWTs as a function of the regional multi-day air temperature index, as follows (updated here with the relevant air and water temperature datasets for the Cowichan system):

Equation 1: $T_w = \alpha + \beta * T_a$; where

T_w = *estimated mean water temperature (MWT) in the Lower Cowichan;*

T_a = *SHAWNIGAN LAKE 7-day mean air temperature index (MAT); and*

α = *y-intercept and* β = *regression coefficient.*

Equation 2 : $T_w = \mu + (\alpha - \mu) / (1 + e^{\gamma(\beta - T_a)})$; where

T_w = *estimated mean water temperature (MWT) in the Lower Cowichan;*

T_a = *SHAWNIGAN LAKE 7-day mean air temperature index (MAT);*

α = *estimated maximum water temperature;*

μ = *estimated minimum water temperature*[18]*;*

γ = *steepest slope of the function; and*

β = *air temperature at the inflection point.*

The existence of hysteresis[19] in a water body, and the resulting need to use separate warming and cooling season regression models to describe air/water temperature relations at a particular site, was evaluated for both linear and logistic models. In the linear approach, an additional categorical "season" predictor was a significant effect (signifying different seasonal model intercepts), and/or whether there was a significant interaction effect with air temperature, indicating significant differences in seasonal model slopes (i.e., $P < 0.05$ for the Type III model sum of

[18] At freezing latitudes/altitudes, parameter μ may be set to zero (i.e., dropped). Since the Cowichan site falls within the lower altitudes of the pluvial coastal climate zone with mean minimum daily winter temperatures above 0°C, parameter μ was retained.

[19] Hysteresis: the heat storage properties of water. Hysteresis is a measure of the seasonal effect of the differential rates of heat exchange between air and water as the spring-to-summer period warms up and the fall-to-winter period cools down (Wetzel 1975). The observed pattern of hysteresis is related to the complex physics of air-water heat exchange processes. These involve evaporative cooling of the lake in the late summer-to-fall, thermal de-stratification in the fall-to-winter; rapid, wind-induced, mixing of surface and deep waters through the winter, and initiation of thermal stratification and evaporative cooling once again in the spring-to-summer season.

squares (SAS 2008). For the logistic analysis, hysteresis was assessed by comparison of the *Nash-Sutcliffe Coefficient* (NSC) value for the all-season model versus the averaged NSC values for the separate warming and cooling season models (Mohseni et al. 1998):

Equation 3: $Hysteresis = [(NSC_w + NSC_c) / 2 - NSC_{all}] \geq 0.01$; where

NSC_w = NSC for warming season;

NSC_c = NSC for cooling season;

NSC_{all} = NSC for all seasons combined;

Water Temperature Time-Series Reconstruction

MODEL CALIBRATION

Linear and logistic regression relations described above were developed using site-specific daily mean water temperatures (MWTs) from the sub-daily[20] dataset for the Lower Cowichan River as a function of the regional air temperature index (7-day centered SHAWNIGAN LAKE MAT variate).

Model calibration data were selected based on examination of annual air and water temperature time-series and correlation plots. A minimum of 5 years of representative data, including sufficient observations at the upper end of the temperature range for both warming and cooling seasons, were obtained from source datasets partitioned as follows:

Reference Site	Calibration Years	Validation Years
Lower Cowichan	2002, 2004, 2006-2011	2000-2001, 2003, 2005

The warming and cooling seasons were first distinguished from each other by determining the seasonal temperature "turn-around point" (i.e., the timing of the winter season turn-around point was not required for the purpose of this analysis)[21]. The seasonal transition dates were obtained by plotting weekly mean daily water temperatures as a function of weekly mean daily air temperatures, and connecting

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[20] Observed water temperature data were classified into three categories based on temporal data resolution (Hyatt et al. 2015):

- Class 1: Automated date-specific data summarized from multiple sub-daily samples evenly spaced over a 24-hour period;
- Class 2: Daily mean values, derived from automated data summarized from date-specific samples, though of unknown frequency and/or interval; and
- Class 3: Instantaneous and possibly routine date-specific "spot" samples, taken at a specified or unspecified time of day, but most likely during daylight hours, and therefore systematically biased.

Class 1 datasets provide the highest resolution and least potential bias, and are therefore the most appropriate data for statistical use in site-specific air-to-water and inter-site water-to-water temperature relationships. Class 2 and Class 3 data may be used to extend these Class 1 time-series, but only if the data are found to be statistically equivalent, using parametric comparisons tests (e.g., ANOVA, paired t-tests).

[21] For linear models, an additional "winter" season was defined for the linear analysis (November 25th to March 10th), encompassing the cold-weather months when changes in air temperature are not reflected in changes in water temperature due to hysteresis effects at low temperature extremes.

the points chronologically. The week associated with the maximum mean air temperature, indicating the ending of the warming season (and the starting point of the cooling season) was converted to day-of-year to pinpoint the seasonal turn-around date. Since the same regional air temperature index is used for all Cowichan water temperature reference sites, the same seasonal turn-around point applied to all locations, and for both linear and logistic models.

Model Validation

Site-specific linear and nonlinear air/water regression parameter estimates were tested for statistical significance, and applied to the Shawnigan Lake air temperature index to estimate reference site daily MWT for the period of record of air temperature data. Modeled MWTs for the validation dataset were correlated with observed reference site water temperature data, graphically and statistically, as a measure of goodness-of-fit. The all-year Pearson and Spearman correlations for the validation years were compared between model types to determine whether linear or logistic outputs best simulated observed MWTs at the Lower Cowichan River reference site.

Trend and Exceedance Analyses

Water Temperature

Mean estimated water temperature in the Lower Cowichan was calculated for the Chinook migratory period (September - November) for each year and plotted to examine long-term trends (1920-2012) in water conditions. Regression statistics were reviewed for significance of the trend for the duration of the time-series.

For migrating adult Chinook salmon, water temperatures above 17°C ($POT_{17°C}$; i.e., peak-over-threshold > 17°C) are considered stressful (Salinger and Anderson 2009, McCullough 1999). Modeled water temperature estimates were analyzed for the frequency of dates in each year and month (September-November) for which mean daily water temperature exceeded this threshold value, and summarized by decade.

In addition, the frequency of annual periods in which water temperature continuously exceeded the threshold, and the mean duration (days) of these periods, was derived for each year. These data were summarized by decade to review trends in the frequency and duration of continuous periods of stressful temperature conditions.

River Discharge

For discharge, the "exceedance analysis" of interest is for "low flow" dates (i.e., the frequency of dates for which flow in the Lower Cowichan was less than a threshold value of 5 cms, which was identified as the daily discharge level corresponding to a regulated minimum discharge of 7 cms in the Upper Cowichan). Discharge data were thus analyzed for the frequency of dates in each year and month (September-November) for which mean daily discharge did *not* exceed this threshold value, and summarized by decade. In addition, the frequency of annual periods in which flow levels continuously remained below the threshold, and the mean duration (days) of these periods, was derived for each year. These data were summarized by decade to review trends in the frequency and duration of continuous periods of barriers to upstream migration.

Mean daily discharge (observed + estimated) during the Chinook migratory period in the Lower Cowichan was calculated for each year and plotted to examine long-term

trends (1913-2012) in flow. Regression statistics were reviewed for significance of the trend for the duration of the time-series.

Migration, Temperature and Discharge

Daily mean water temperature and discharge time-series were merged with daily Cowichan Chinook migration rate data for co-variation analyses, without date lags.

To characterize the temperature and discharge conditions during historical stock migration, frequency distributions of observed active migration dates (i.e., filtered for non-zero migration rates) at varying levels of temperature, discharge, and both temperature and discharge, were generated. By simply tallying the number of dates in the historical dataset at which some migratory activity occurred, these plots indicate the general distribution of temperature and discharge conditions that were available during the migratory period.

A similar frequency distribution of active migration dates, weighted by the daily migration rate, indicates how much migration occurred at a given temperature, discharge, or temperature-and-discharge combination. In contrast to the simple distribution of dates of migration, these plots indicate which temperature and discharge conditions are associated with highest migration rates (i.e., presumably most favourable to salmon migration), and, by extension, the thermal and hydrological limits (if any) that differentiate high versus low rates of migration. The influence of experimental pulse flow releases on migration rate was examined by repeating this analysis after omission of pulse flow dates.

To further compare pulse flow discharge levels versus natural flow levels on migration rate, migration data were classified as 'Pulsed' or 'Natural' based on dates of pulse experiments (Table 4), and binned in four flow categories[22]: 0-8; 8-16; 16-22; and >22 cms for statistical means comparisons.

Environmental "limits" derived from the weighted frequency analyses were used to set threshold values for calculation of daily deviations in the modeled water temperature and discharge time-series, and combined with deviations in daily Chinook migration rate on annual anomaly plots to examine the pattern of daily variation in each time-series in relation to each other.

The anomaly threshold ("zero-line") for migration data was set to the 50th percentile of the historical daily migration rate (0.75% of annual total escapement) to distinguish between "significant" (positive anomalies) and negligible or "insignificant" (negative) migration. The migration threshold value was subtracted from the historical daily migration rates to derive the anomaly for daily migration.

River discharge of 10 cms was used as the zero-line threshold, and the water temperature threshold was set to 18°C, based on approximate upper thresholds for migrating Chinook salmon. The difference between these thresholds and the site-specific daily mean temperature and discharge estimates were plotted on a common axis (discharge rates were factored by 0.1 to fit on the y-axis).

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[22] Hop Wo et al. (2005) found that pulse flows of 16 cms or more were most conducive to significant migration.

RESULTS

CHINOOK MIGRATION DATA

The present population of fall run Chinook was experiencing a declining trend since 1996, to an historic low in 2009 of 785 adult and 281 jack Chinook, including 293 adults that were captured in the lower river and truck to the spawning groups due to low water conditions. Annual escapements since 2010 have rebounded to 4,000+ large adults. As a result of this recent improvement, the level of decline no longer meets COSEWIC[23] standards for classification of the stock as "endangered".

Cowichan Chinook data (total of adults from fence counts) indicate migration typically commences in early September and terminates by mid-November (Table 1). Non-zero migrant counts averaged approximately 68 ± 157 fish per day; maximum daily counts surpassed 1,600 fish. Ninety-five percent of daily counts are less than 354 fish, and the median estimate for the all-year dataset is 17 fish per day.

The corresponding all-year mean daily migration rate was 2% of total annual escapement, with time-to-50% occurring on day 279, approximately October 6th (
Figure 3). Annual peak daily rates are typically in the range of 35-40%; as much as 51% of the annual escapement occurred on one day in September 2011 (Table 1).

Annual time-series of Cowichan Chinook daily migration rates (%) are plotted in Appendix A along with mean and maximum daily migration rates across all years, 1988-2014.

DISCHARGE DATA

Observed daily mean discharge data obtained from WSC archives are summarized for the *Lower Cowichan River* for all months, and for specific active migration months (August-November) in Table 2 - Table 3. Lowest flows occur in August and September, just prior to the active Chinook migration period (Figure 4, Figure 5). Extreme low flows in the lower Cowichan dip below 4-5 cms (lower 5th percentile) (Table 3).

Strategies for timed artificial pulse flows from Cowichan Lake storage, during periods of upstream migration, have been employed in most but not all years since 1988 (Hop Wo, Nagtegaal, and Carter 2005); the date and approximate maximum rate of artificial pulse flow events is tabulated in Table 4.

Estimating Missing Lower Cowichan River Discharge

Missing daily flow data in the *Lower Cowichan River* were estimated from the relationship with the historical *Upper Cowichan River* data (excluding experimental pulse flow dates: Table 4) based on linear and non-linear models. Cross-correlation analysis based on calibration data sub-sampled from 10% of the available data indicated relatively high non-parametric Spearman correlations between discharge at the Cowichan stations based on all-season data ($r_S = 0.99$, $P < .0001$, $n = 1,782$;

[23] Committee on the Status of Endangered Wildlife in Canada.

Table 5; Figure 6). Linear regression analysis indicated a significant relation (r_P = 0.98; P < .0001; n = 1,766; Figure 7). However, the regression output also indicated a significant lack of fit in the error term (P < .0001), evidence of heteroscedastic non-linearity in the residuals.

The transformation of the data into a log-linear relationship further improved the correlation (r_P = 0.99, P < .0001, n = 1,782) and regression relation, relative to the linear analysis, as indicated by the insignificance of the lack of fit term (P = 0.33) (Figure 9). A curvilinear polynomial analysis yielded no further improvements to the fit, and thus the log-linear model ($Y=aX^b$) was identified as the most parsimonious.

> Equation 4: *Lower Cowichan* (cms) = $0.618x^{1.15}$; where x = *Upper Cowichan* discharge (cms)

Spearman correlation analysis comparing observed and estimated *Lower Cowichan River* discharge rates indicated a significant relation: r_S = 0.99 (P < .0001, n > 20,000). Annual plots of observed *versus* estimated flows (Figure 10) indicated the log-linear model reasonably estimates variation in observed lower Cowichan autumn flows.

WATER TEMPERATURE DATA

Lower Cowichan River

Water temperature data obtained from the Catalyst pump-house site are summarized in Table 6 (all-seasons) and Table 7 (active migration period only). The annual time-series are plotted in Appendix A and condensed in Figure 11. Thermograph plots by year (Figure 12) and all-year mean daily values ± two standard deviations (Figure 13) indicate maximum temperatures occur in early August, and may surpass 20°C from July to early September, but are generally closer to 15°C during peak Chinook migration in October.

Water Temperature Time-Series Reconstruction

Reference air temperature data from ENVIRONMENT CANADA'S *Shawnigan Lake* meteorological station indicated mean historical July-August temperatures (1981-2010) of 18°C, falling to 15°C in September and 10°C on average in October (Figure 14). Total monthly precipitation typically increased from a low of ~20-30 mm in summer to 115 mm in October and double that in November (~230 mm), corresponding to an eight-fold rise in Cowichan River flows from ~10 cms to ~80 cms in early winter (Figure 5).

Seasonal Turn-Around Point

The mid-year seasonal temperature turn-around point for all reference sites was in week 30 – approximately day 210, or July 29th – based on maximum mean weekly air and water temperatures (Figure 15). The "warming season" is therefore from January 1st to July 29th, followed by the "cooling season" from day 211-329, i.e., July 30th – December 31st.[24]

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[24] The "winter" seasonal turn-around point was January 1st, but data between late November and early April were not used in this analysis.

Multi-Day Air Temperature Index

The multi-day *Shawnigan Lake* air temperature index that best correlated with all-year daily mean water temperature was identified as the 7-day centered moving average air temperature index (7d-CMAT). The 7d-CMAT scored the highest correlation for Lower Cowichan water temperatures in the cooling season, relative to the 3d-, 5d-, 10d-, and simple daily MAT air temperature indices (Figure 16). The 7D-MAT provided the best trade-off between maximizing correlation and minimizing the effects of multi-day averaging on predictive power at longer period lengths. Thus, the *Shawnigan Lake* 7d-MAT was used for subsequent air/water temperature analyses.

Model Calibration and Validation

Logistic and linear air/water temperature models were parameterized using a subset of the available data for calibration, and tested for goodness-of-fit against the remaining years for model validation. Calibration and validation data years, and the number of observations available for analyses by season, are identified for the Lower Cowichan watershed reference site in Table 8.

Hysteresis at each site was evaluated by comparing Nash-Sutcliffe coefficients (NSC) for all-season logistic models fit to the calibration data against the average NSC for seasonal models. Hysteresis was detected at all sites, indicating the site-specific air/water temperature relationships were best modeled using separate seasonal models (Figure 17). Seasonal model parameters, 95% confidence limits, and NSC goodness-of-fit coefficients are listed in Table 9.

Linear regression model output for seasonal air/water temperature relationships and calibration data are provided in Table 10. Type III sum of squares for a season effect and a season/air temperature interaction effect are highly significant in all three cases, indicating again, that hysteresis exists and that seasonal models provide the best fit to the data (Figure 18).

Predictive estimates of daily mean water temperature were generated for each site, model type and season for the extent of the air temperature record. Correlation analyses between observed and predicted daily MWT values for the validation years were used to compare the predictive skill of logistic versus linear models. Season-specific Pearson (least squares) and Spearman (rank) correlation coefficients for the validation data are contrasted in Table 11. Validation data correlations indicate minor but insignificant improvement of logistic models over linear models for estimating daily mean water temperatures. As the nonlinear model has a predictive advantage at temperature extremes, the seasonal logistic model parameters were selected as the best estimators of daily mean water temperature at each site, and were used to reconstruct historical daily water temperature estimates for the period of available air temperature data. A subset of the validation data years with observed and modeled MWT output, along with daily MAT and the 7-d MAT index, are plotted in Figure 19.

TEMPERATURE, DISCHARGE AND MIGRATION

Trends in Water Temperature

Mean water temperature in the Lower Cowichan during September-November (estimated from seasonal logistic regression model relationships with air

temperature) has been trending in a slightly positive direction since 1920 (b = 0.0097; r^2 = 0.004, P < .0001; Figure 20), suggesting an increase in average water temperature conditions during the migratory period over the last century of almost 1°C.

Trends in Discharge

The long-term trend in observed and estimated daily mean discharge in the Lower Cowichan was also weakly significant (b = 0.136; r^2 = 0.005; P < .0001) for the Chinook migratory months (Figure 21). This corresponds to an increase in average flows during the September - November migratory period over the last century of 14 cms, or approximately 1.4 cms per decade.

Migration in Relation to Temperature and Discharge

Frequency analysis of historic Cowichan Chinook non-zero migration dates indicated that almost 40% of migration activity occurred at Lower Cowichan flow rates of 5-7 cms (47%), and ~60% of all migration dates were characterized by flows of < 10 cms (Figure 22). Mean daily migration rates at flows of < 10 cms were 1.0-1.6%. High average rates of migration (3-5% per day) appeared to require flow rates of at least 10 cms – with maximum migration rates occurring at 16-22 and 30-36 cms (Figure 23). The nearly bi-modal distribution of the "preferred" discharge levels for migration (Figure 23) likely indicates the effect on migration of pulsed flow releases in 21 of the 27 years of data (Table 4), versus natural flow increases. The lower mode (16-22 cms) appeared to be associated with pulsed flows ranging from 7-30+ cms (mean 17 cms), generally released during extended low flow periods (and warm water conditions, as described below). The upper mode (30+ cms) conformed largely to late season (and cooler) water level increases due to precipitation.

Similarly, the distribution of daily water temperatures at which Cowichan Chinook migrated differed somewhat from the rate of migration at those temperatures. Though a wide range of temperature conditions were utilized by migrating fish, most commonly in the 13-18°C range (Figure 24), highest Chinook migration rates occurred at 13-15°C (Figure 25). The apparent bimodal distribution of temperatures utilized by migrants (Figure 24) contrasts with the unimodal distribution of "preferred" temperature conditions for migration (Figure 25), indicative again of the frequent application of pulsed flow augmentations over 78% of the years of data. In this case, the lower mode likely represents the optimum migration conditions found under natural flow regimes late in the season when temperatures have dropped to 15°C or less, whereas the upper temperature mode at 16-18°C corresponds largely to pulsed flow conditions, which stimulated migration despite higher temperatures.

Weighted frequency analysis of Chinook migration rates at all combinations of discharge and temperature[25] further illuminated the interaction of these environmental factors on migration. The two-dimensional distribution of migration rates reflected a "preferred migration environment" at flows in the 25-30 cms range at water temperatures of 13-16°C and an evident lesser mode at lower discharge levels (15-16 cms) and higher temperatures (17°C) (Figure 26, Figure 27). Omission of pulse flow dates from the analysis – thereby restricting analysis to natural flow

[25] Omitting infrequent cells, where n < 3.

regimes – largely eliminated the lesser mode at 17°C and 15 cms (Figure 28), emphasizing the specific temperature and discharge conditions favouring migration past the fence during controlled flow releases (Figure 29).

When partitioned by flow type (natural *versus* pulsed), an improvement in mean daily migration rate was apparent under pulsed flow conditions at low and mid-flow categories. Discounting flow levels above 22 cms, for which accurate Chinook counts are not consistently available across all years, means comparisons indicated a significant doubling of daily migration rates during pulse flows as well as increased migration rates as discharge category increases from 0-8 to 8-16 cms ($P_{KW} < .001$; Figure 30; Table 12). Natural migration rates were more at par with pulsed migration at flow levels of 16-22 cms.

Pulse flow effects on daily mean migration rate were also highly significant across water temperature categories (Figure 30). Sub-grouping by flow category reinforced the evidence that migration rates were most consistently improved under pulse releases at flows up to 16 cms (Figure 31; Table 13). Natural high flows were most associated with high migration rates at the lowest temperature levels.

A subjective review of the annual migration and environmental variable anomaly plots based on 10 cms and 18°C thresholds (Appendix B) illustrated the within-year relationship between migration rates and flux in discharge and water temperature. Basically, significant migration rates only rarely occurred at flows less than 10 cms and water temperatures greater than 18°C.

For example, a "temperature-effect" on migration anomalies was most apparent in years with extended "low flow" periods (<10 cms)[26] such as 1989, 1995, 2006, and 2009, where migration rates demonstrated a reversal in sign most frequently in the temperature anomaly range of -1°C to 1°C (i.e., 17-19°C), in the absence of significant changes in flow levels. In 1995, for example, migration attempts in mid-September appeared to have been curtailed by high temperatures of 18-20°C, and reached significant rates only when temperatures dropped to 17°C or less in early October. Where significant migration was evident at temperatures >17°C, it was either accompanied by a natural or pulse increase in flow and generally not sustained for more than a day or two (e.g., 1990, 1991, 1994, 2002, 2008, 2009, 2012). In some cases, it appears that significant migration rates were initiated during falling temperatures associated with precipitation that did not significantly raise flows (e.g., 1989, 1995, 2000, 2014).

Low temperatures alone were often not sufficient for significant migration to occur. Evidence that, in the absence of limiting temperatures, increases in flow[27] are key to stimulating Chinook migration were found in nearly all years: 1988, 1991-1994, 1997, 1998 and 1999 (natural flows in October), 2000-2005, 2008 (natural flows in late September), 2010 (natural flows in October), 2011, 2012, 2013, and 2014. There do not appear to be any instances where improved flows (>10 cms) were not

[26] The temperature relation is also apparent in more moderate flow years, though the signal is not as easily distinguishable from potentially interacting positive flow effects (e.g., 2001, 2005-2009).
[27] Flow increases are all associated with "artificial pulse" flow releases from storage behind the Cowichan Lake dam (Table 4) except where noted in the text.

associated with "significant" migration, at least during the period of most frequent historic migration (late September to late October)[28].

Instances of high migration not associated with flow increases were less frequent, and were all characterized by low temperatures (<16°C) late in the migratory period (mid-to-late October): e.g., 1989, 1993, 1995, 1996, 2006 and 2009 (late September)[29].

Temperature Exceedance Analyses

A frequency analysis of estimated daily mean water temperature indicated the cumulative total number of $POT_{>17°C}$ dates per year appears cyclically variable, with peaks in the 1940s and 1990s (Figure 32). The combined average number of $POT_{>17°C}$ dates across all migration months (September-November) fluctuated around 10-12 days per year between the 1960s and 1980s but jumped to 17-19 days in the past two decades (Figure 32, Table 14), but indicates no significant trends ($(P_{KW} > 0.15)$.

The length of $POT_{>17°C}$ events during Chinook migration has increased from an average of ~18 ± 20 days in the 1960s-1970s to ~25 ± 30 days in the 2000s, concurrent with an increase in the decadal total frequency of $POT_{>17°C}$ periods of that length from ~37-39 to 53 (Figure 33, Table 14). Annual variability remains large with no statistically significant trend in evidence.

Discharge Exceedance Analyses

Frequency analysis of the decadal mean number of "low flow" dates (i.e., $POT_{<5\ cms}$) per month (July-November) in the Lower Cowichan River indicated the apparent benefits of weir installation in the late 1950s on flow levels, with a significant drop in low flow events in the 1960s and 1970s (Figure 34). However, the number of low flow events has increased to approximately 20 per year since the 1980s, mostly in August and September. Again, inter-annual variability masks any temporal trend in exceedance events ($P_{KW} > 0.20$).

Average length (days) of $POT_{<5\ cms}$ events reached an historic low in the 1970s (7.1 ± 9.7 days per event for 25 low flow periods in the decade), but has almost doubled, to 13.1 ± 22.8 days per period in the 2000s based on 26 low flow periods in the decade (Table 15). The current duration of low flow periods, on average, appears to be still less than recorded prior to the weir installation (Figure 35). The decadal mean duration of low flow periods during the 1940s was significantly greater than all decades since ($P < .001$).

DISCUSSION

Maximum daily migration rates[30] for fall Chinook were associated with moderate

[28] One case where a pulsed release was not associated with an increase in migration was in early September 2008, most likely due to the pulse occurring in advance of Chinook run timing.
[29] In 2006 and 2009, escapements were <200 fish, and, therefore, "significant" escapement rates were not significant in terms of absolute numbers of fish.
[30] Daily migration rate is expressed as the number of large adults enumerated through the counting fence relative to the annual total fence counts of large adults.

temperatures (13-15°C) and discharge levels (16-32 cms) in the lower Cowichan River since 1988. Of these two environmental co-variates, discharge appears to be the most influential, and potentially limiting, on upstream migration. While over 60% of migration dates occurred at 15°C or lower and 80% at temperatures well within the tolerance range for upstream migration (<17°C), only 20% of dates of migration activity occurred at the "preferred" discharge levels. While very few days (5%) occurred during migration when temperatures exceeded the 20°C threshold associated with "stop" migration events (Goniea et al. 2006), the majority (60%) of all dates during the migratory period were characterized by flows of 10 cms or less. The 50th percentile of flows during peak migration (September-October) was 8.2 cms.

At flows < 10 cms, average daily migration rates were low (1.6% or less). Comparatively high average migration rates (3-5% per day) occurred at flows > 10 cms, with bi-modal peak migration rates at 16-22 cms and 30-36 cms (Figure 23). The apparent bi-modal distribution of the "preferred" discharge levels for migration likely indicates the effect on Chinook migration of controlled "pulsed flow" releases from the CATALYST PAPER CORP. weir at Cowichan Lake versus unregulated natural flow increases following fall rain storm events. The lower mode (16-22 cms) appears to be associated with the regulated flows ranging from 7-38 cms (mean 17 cms; Table 4), generally released during extended low flow periods and warm water conditions. The upper mode (30+ cms) conforms largely to late season (and cooler) water level increases due to fall precipitation events.

Experimental Flow Augmentation

Experimental flow augmentation to stimulate adult Chinook migration via controlled releases have occurred almost annually since 1988, and were extended after the drought of 2003 to provide more favourable Chinook passage conditions in the lower river when adequate water storage was available. Pulse flow releases appeared to positively influence migration, often stimulating a large proportion of the total spawner population to pass through the counting fence in a period of one to several days.

The effects of flow augmentation may be partially masked in univariate analyses[31], but were clearly represented in this study by the lesser modal peak in migration at average water temperatures of 17°C (*cf.* Figure 27, Figure 28, and Figure 29).

Hop Wo et al. (2005) found statistically-significant increases in the movement of Chinook upstream during the 48 hours post-pulse relative to the 48 hours prior to water releases. The authors estimated a peak daily discharge of 16.1 cms for 48 hours as the minimum effective pulse flow to stimulate migration and enable continuous upstream movement to the spawning grounds, but indicated that other factors, such as weather (e.g., temperature and precipitation events) were likely confounding elements. The authors suggested that *timing of early pulses* must be a factor, too, since fish must be present to respond.

Given that migration rates under pulsed flow conditions were consistently higher

[31] e.g., the distribution of "preferred" migration (Figure 25) is unimodal around 13-15°C, and does not reveal the association of pulse flows with high migration at warmer temperatures (16-18°C) evident in Figure 25 and delineated in Figure 27.

across all temperature categories relative to natural flows in the low- to mid-range flow levels (up to 16 cms), management decisions regarding synchronizing flow augmentation with the presence of holding fish appeared to be generally reasonable. However, it has been largely unclear what proportion of Chinook holding in the marine environment was stimulated to migrate as a result of a given pulse. For example, in 2011 over 50% of the total annual fence count was observed passing the fence on one day, during a scheduled pulse event. It is unknown, though, whether that migration pulse represented 100% of fish present (implying high effectiveness and low delay stress) or, alternatively, 50% of all fish present (i.e., only half of the fish migrated), suggesting potential delay impacts on the remaining holding fish.

Regarding the fish that choose to migrate as a result of flow augmentation, Hop Wo et al. (2005) were unable to resolve how far upstream the fish moved as a result of pulse flows, or the ultimate fate of the migrants. Neither the effects of artificial migration stimulation under warm water conditions on the biology and reproductive condition of Cowichan Chinook, nor the ultimate fate of the migrating fish, have been studied in detail. On the benefit side, it is evident that pulsed flow augmentation enables some Chinook to move into freshwater, reducing seal predation mortality in the harbour. But by moving fish into upstream holding areas, are they then equally at risk from other predators, fishing mortality, and warm water temperatures[32]? Questions therefore remain regarding the risk/benefits of flow augmentation, since a comprehensive analysis has not been conducted.

Further analysis, based on data partitioned into pulsed versus natural flow regimes, would be required to determine whether there is evidence that water temperatures become a limiting factor, even at higher flow levels, and whether the highest sustained migration rates, which appear to be associated with *natural* flow increases later in the season (Figure 27), are simply a function of timing, as fall rains and falling temperatures coincide with the biological urge of sexual maturation, driving most fish to naturally complete migration at that time. Future tagging operations in association with flow augmentation experiments would assist in resolving some of these issues.

Trends in Environmental Conditions

Long-term trends in water temperature and flow levels during the freshwater Chinook migratory period (September-November) were only weakly apparent in the Cowichan River over the last 50 years, amounting to seemingly minor increases of approximately 1 cms of flow and 0.1°C of temperature per decade. Small increases in average temperature, however, appear to be manifesting in a 50% increase in the number and continuous duration of dates when water temperature peaks over 17°C during the migratory period since the 1960s.

Long-term natural trends in Cowichan river discharge levels are obscured to some

[32] Anecdotal evidence of thermal refugia via groundwater seeps along the Cowichan River (pers. comm., M. McCulloch, BC Min. Environment) has not been substantiated to date by temperature sampling at depth, which indicated a maximum of 0.6°C difference between surface and river bottom in between Skutz Falls and Road Pool in July 2013 (unpub. data, J. Damborg, BCCF).

extent by increasing water demand for domestic and industrial purposes in the watershed. Flow controls established in the 1950s at the lake outlet appeared to assist in reducing the frequency of extreme low flow (< 5 cms) events in the lower river in the 1960s and 1970s. However, the number of low flow dates has largely doubled in late summer since the 1980s, mostly as a result of incursions of drought into September and October corresponding to a doubling of the average continuous duration of low flow periods, despite a slight positive trend in autumn discharge. If these trends continue into the future, the frequency and magnitude of delays to fish migration are likely to increase.

Migratory conditions in 2014 might serve as an indicator of the possibilities ahead.

> *Due to warm winter conditions, there was no snow pack in January, and snow accumulations in February and March were half of the average. Due to competing interests, water managers failed to obtain permission[33] in April to store lake water, such that by early June, discharge projections indicated concerns with respect to satisfying both fisheries flows and water supplies for the Crofton Mill through the summer. CATALYST requested and received permission to drop the summer discharge base flow from 7 to 5 cms, and then 4.5 cms until fall. However, there was no water "in the bank" to do a pulse flow.*
>
> *Migration delays were observed. Though some Chinook were able to migrate upstream during the low discharge in September, they stopped short of the fence and held in two locations.[34] The fish delayed for several weeks, experiencing water temperatures of 18-19°C (see 2014 in Appendix B), until fall storms finally arrived in mid-October, at which point the fish migrated out of the holding areas and into the lake over a four day period. Accurate daily counts became untenable as the rising waters rapidly submerged the fence.*

While temperature conditions currently appear to be within migration tolerance range for this stock, regional climate changes which are expected to bring hotter, drier summers are likely to exacerbate low flow conditions. Projected regional hydrological impacts of milder, wetter winters – and the corresponding reductions in regional snowpack due to a shift to pluvial weather patterns – will likely exacerbate existing competing water demands from domestic, agricultural, and industrial users. The consequences to adult fish migration likely involve a reduced window of upstream migration timing due to delays in upstream migration and increased predation effects in the marine environment. These pressures may favour later timing of migration, with potential consequences for the next life history stages of spawn timing and egg incubation.

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[33] Authority over flow control structures and issuing of water storage licenses lies with the Provincial Ministry of Forest, Lands and Natural Resource Operations.

[34] Holding locations: Riverside (just downstream of the fence) and JC's, below the Silver Bridge.

RECOMMENDATIONS

1. Extend the retrospective pulse flow analysis (Hop Wo et al. 2005) to include pulse flow experiments since 2004 to quantitatively evaluate the extent to which pulse flows have been effective in stimulating Chinook migration past the adult counting weir.
2. Investigate fish passage at Skutz Falls, and the efficacy of the fishway at various flows and water temperature levels, to provide greater insight into Chinook migration behaviour and holding patterns upstream of the counting fence. This could be accomplished with the use of PIT tag[35] studies.
3. Supplement PIT tag observations with continuously recording archival time and temperature tags (e.g., Fryer et al. 2011) to provide insight into fish behaviour and duration of exposure to specific conditions of temperature and oxygen in the Cowichan estuary and the availability and use by Chinook of freshwater thermal refugia related to groundwater sources.
4. Perform a tagging experiment to evaluate, in the absence of pulse flow interventions, the mortality and survival consequences for Chinook holding for extended periods near the mouth of the river.
5. Design a series of controlled pulse flow experiments to further investigate the conservation risks and benefits of flow augmentation strategies on enabling Chinook migration. Incorporate elements of Recommendations 1-4 to quantitatively assess downstream and upstream migratory effects due to flow augmentation, such as estimating the proportion of fish remaining in the marine environment post-pulse; and tracking the movements of fish upstream under various environmental conditions.
6. Assemble and analyze environmental and biological data during spawning and early life history stages to quantify environmental impacts on Cowichan Chinook spawn timing, reproductive success, incubation and fry emergence timing, and fry/smolt production.
7. Implement a "Fish and Water Management Tools" project (Hyatt & Stockwell 2003; 2013) to develop a set of decision support models to improve the basis for seasonal water management decisions that influence annual production variations of Cowichan Chinook.
8. Forecast, based on down-scaled climate model outputs, potential changes in the frequency and duration of migration delay events due to changing thermal and hydrological conditions in the Cowichan watershed under a range of future climate scenarios.
9. If investigations above support controlled flow augmentation as a viable migration enhancement method, and thermal barriers are projected for future decades, investigate cost effectiveness of cold-water release methods based

[35] PASSIVE INTEGRATED TRANSPONDER (PIT) tag studies may be used to track the movements of tagged fish past full-stream dual antenna arrays above and below Skutz Falls, as well as other key locations in the watershed (e.g., Pellett et al. 2015).

on obtaining water from the cooler depths of Cowichan Lake.

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Figure 35. Mean length (days) and frequency of "low flow" periods in which *Lower Cowichan* discharge (observed + estimated) continuously remained below 5 cms, by decade. Average length of $POT_{<5cms}$ events reached a historic low in the 1970s (7.1 ± 9.7 days per event for 25 low flow periods in the decade) but has increased to 13.1 ± 22.8 days per period in the 2000s (based on 22 low flow periods in the decade). Note: no discharge data available for the 1920s and 1930s. 66

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Appendix A. Multi-panel plots of daily Cowichan Chinook migration in relation to environmental variables, by year, 1988-2012. 67

Appendix B. Annual anomaly plots for Cowichan Chinook migration, water temperature (estimated), and river discharge (flow factored by 0.10 to fit on y-axis). Zero-line thresholds: (a) Daily migration rate = 0.75% (50^{th} percentile of non-zero daily migration rates (1988-2012, 2014); (b) Lower Cowichan water temperature = 18°C; (c) Lower Cowichan discharge = 10 cms. See also Table 4 for documentation of annual pulsed flow timing. 83

TABLES

	Cowichan Fence											
	Date			Chinook Migrants				Migration Rate (%)				
	Date Count	Min Date	Max Date	Min	Mean Daily	Max Daily	Annual Total	Mean Daily	P50	P75	P95	Max Daily
Year												
1988	51	11SEP	02NOV	1	101	592	5,164	1.96	1.01	2.17	7.67	11.46
1989	37	14SEP	22OCT	1	36	145	1,324	2.70	2.04	3.78	7.85	10.95
1990	43	13SEP	25OCT	1	97	634	4,164	2.33	0.89	3.12	9.01	15.23
1991	58	26AUG	03NOV	1	37	265	2,129	1.72	1.29	2.35	4.18	12.45
1992	65	19AUG	30OCT	1	119	1,251	7,740	1.54	0.37	1.16	10.21	16.16
1993	87	23AUG	22NOV	1	58	637	5,058	1.15	0.26	0.71	7.75	12.59
1994	78	18AUG	13NOV	1	63	1,676	4,890	1.28	0.32	0.92	5.97	34.27
1995	42	08SEP	19OCT	6	231	1,600	9,715	2.38	1.24	2.60	8.92	16.47
1996	56	30AUG	24OCT	3	183	1,207	10,271	1.79	0.49	2.20	8.74	11.75
1997	25	07SEP	01OCT	5	176	1,028	4,401	4.00	1.77	3.57	18.34	23.36
1998	63	06SEP	08NOV	1	69	783	4,328	1.59	0.42	1.39	7.07	18.09
1999	63	27AUG	30OCT	1	61	553	3,836	1.59	0.76	1.41	7.48	14.42
2000	45	08SEP	24OCT	1	103	678	4,640	2.22	0.54	2.82	9.42	14.61
2001	56	06SEP	31OCT	2	60	581	3,350	1.79	0.61	2.28	6.66	17.34
2002	68	04SEP	12NOV	1	41	559	2,766	1.47	0.72	1.45	4.16	20.21
2003	38	08SEP	16OCT	1	36	526	1,352	2.63	0.33	0.74	14.35	38.91
2004	48	10SEP	27OCT	1	42	405	2,002	2.08	1.07	2.35	6.79	20.23
2005	49	07SEP	26OCT	1	27	159	1,302	2.04	0.77	2.61	8.83	12.21
2006	42	07SEP	26OCT	1	4	11	179	2.38	2.23	3.35	5.03	6.15
2007	29	06SEP	05OCT	1	12	60	350	3.45	2.86	4.57	13.43	17.14
2008	54	04SEP	28OCT	2	19	128	1,003	1.85	1.03	1.99	5.98	12.76
2009	39	09SEP	21OCT	1	4	19	173	2.56	2.31	3.47	5.78	10.98
2010	35	08SEP	13OCT	1	41	558	1,429	2.86	0.28	0.63	26.10	39.05
2011	39	07SEP	16OCT	1	60	1,203	2,358	2.56	0.30	0.68	20.27	51.02
2012	51	05SEP	25OCT	1	31	318	1,559	1.96	0.64	1.28	14.95	20.40
2014	37	16SEP	22OCT	2	65	454	2,421	2.70	1.20	2.19	16.32	18.75
1988-2014	1,298	11SEP	22OCT	1	68	1,676	87,904	2.00	0.75	2.04	8.92	51.02

Table 1. Annual migration statistics for Cowichan adult Chinook daily migrants, 1988-2012 and 2014 (filtered for non-zero observations), documenting migration period and length, mean and maximum daily migrant and migration rate (%) estimates, and total escapement.

Flow & Level Data From Water Survey of Canada
Discharge (m3/s) Statistics (Annual)

------ Site=LowerCowichan ID=08HA011 PARAM=Discharge (m3/s) -------

The UNIVARIATE Procedure
Variable: Value (Discharge (cms))

Moments

N	19574	Sum Weights	19574
Mean	52.813538	Sum Observations	1033772.19
Std Deviation	54.647231	Variance	2986.31986
Skewness	1.79398597	Kurtosis	4.51948109
Uncorrected SS	113048406	Corrected SS	58451238.6
Coeff Variation	103.472013	Std Error Mean	0.39059652

Basic Statistical Measures

Location		Variability	
Mean	52.8135	Std Deviation	54.64723
Median	36.8000	Variance	2986
Mode	101.0000	Range	555.62000
		Interquartile Range	67.55000

Tests for Location: Mu0=0

Test	-Statistic-		-----p Value------	
Student's t	t	135.2125	Pr > |t|	<.0001
Sign	M	9787	Pr >= |M|	<.0001
Signed Rank	S	95790263	Pr >= |S|	<.0001

Quantiles (Definition 5)

Quantile	Estimate
100% Max	558.00000
99%	248.00000
95%	161.00000
90%	124.00000
75% Q3	76.50000
50% Median	36.80000
25% Q1	8.95000
10%	5.49000
5%	4.82000
1%	3.21258

Table 2. All-year and all-season discharge statistics for observed data from the *Lower Cowichan River* near Duncan WSC Station 08HA011, 1960-2014.

	Discharge (cms)						Percentiles					
	Dates	Min	Mean	Max	Std	Skew	P5	P10	P25	P50	P75	P95
Year												
1988	91	4.3	39.0	139.0	45.9	1.0	4.9	5.1	6.6	12.3	95.5	122.0
1989	91	4.1	25.9	90.6	27.7	1.0	4.5	5.1	5.4	7.0	35.2	81.7
1990	91	4.9	69.2	283.0	85.6	1.2	5.2	5.5	6.4	19.9	74.4	246.0
1991	91	11.0	35.7	147.0	35.2	1.5	11.5	12.0	12.5	15.8	43.8	112.0
1992	91	4.4	23.9	72.6	21.8	0.6	4.6	4.7	5.0	11.3	47.0	62.5
1993	91	4.9	8.4	17.6	3.4	0.5	5.1	5.1	5.3	6.3	11.6	14.1
1994	91	4.9	21.1	60.0	20.3	0.8	5.0	5.1	5.4	7.3	42.0	56.4
1995	91	4.8	63.7	286.0	79.9	1.3	5.2	5.5	5.9	21.1	136.0	226.0
1996	91	4.7	33.3	109.0	30.4	0.4	4.8	4.9	5.0	11.8	61.0	80.8
1997	91	7.8	71.5	167.0	45.2	0.1	8.1	8.7	26.9	68.8	108.0	145.0
1998	91	4.0	41.2	281.0	72.4	2.0	4.0	4.1	4.2	11.9	14.9	214.0
1999	91	6.0	42.3	181.0	49.6	1.2	6.2	6.3	6.6	15.6	86.5	139.0
2000	91	5.2	23.2	53.2	16.8	0.4	5.6	5.7	6.3	16.7	39.4	49.9
2001	91	5.3	37.7	162.0	43.7	1.5	5.4	5.6	7.0	15.9	46.9	138.0
2002	91	5.0	26.3	182.0	44.6	2.2	5.4	5.6	5.8	6.1	12.7	144.0
2003	82	2.8	65.1	312.0	77.7	1.5	2.9	3.0	3.3	45.4	91.3	234.0
2004	91	3.2	40.0	107.0	35.9	0.7	3.3	3.9	10.0	23.3	85.0	100.0
2005	91	5.0	38.0	117.0	40.4	0.8	5.3	5.3	5.6	15.8	73.3	112.0
2006	91	2.6	66.0	333.0	105.6	1.4	2.7	2.8	3.1	3.5	156.0	304.0
2007	91	5.8	56.9	157.0	43.7	0.4	5.9	6.0	11.1	59.5	89.4	134.0
2008	91	5.8	36.2	111.0	28.3	1.2	9.2	13.9	16.8	25.7	57.5	93.4
2009	91	5.5	77.6	407.0	112.9	1.6	5.6	5.6	5.7	12.2	110.0	342.0
2010	91	4.4	39.7	108.0	33.8	0.3	4.6	4.8	5.3	33.3	71.1	95.5
2011	91	5.7	37.9	193.0	36.4	2.4	5.9	6.0	7.7	37.1	42.9	107.0
2012	91	3.6	36.6	130.0	41.4	1.0	4.0	4.3	5.2	11.2	68.6	126.0
2013	91	8.1	34.2	93.0	19.9	1.3	10.0	15.8	20.1	29.7	38.8	78.2
2014	91	2.8	43.4	148.2	46.9	0.5	2.9	2.9	3.1	6.5	89.5	121.1
All	2448	2.6	41.9	407.0	55.3	2.4	3.7	4.9	5.8	16.1	60.2	148.0

Table 3. All-year fall month (August-November) discharge statistics for observed data from the *Lower Cowichan River* near Duncan WSC Station 08HA011, 1988-2014.

	Pulse Number											
	1			2			3			4		
	Start	End	Flow	Start	End	Flow	Start	End	Flow	Start	End	Flow
Year												
1988	25SEP	28SEP	19.0									
1989	01OCT	02OCT	9.9									
1990	22SEP	26SEP	19.2									
1991	04OCT	09OCT	17.7									
1992	27SEP	05OCT	13.8									
1993	26SEP	02OCT	12.6									
1994	05OCT	08OCT	16.1	17OCT	20OCT	12.5						
1995	22SEP	23SEP	8.7									
1997	17SEP	24SEP	27.2	25SEP	29SEP	38.3						
1999	06OCT	07OCT	19.8									
2000	25SEP	27SEP	18.6									
2001	27SEP	04OCT	17.9									
2002	02OCT	09OCT	16.5									
2003	06OCT	07OCT	10.5	12OCT	13OCT	15.9						
2004	16SEP	23SEP	7.4	24SEP	28SEP	14.1	29SEP	05OCT	14.8	09OCT	15OCT	22.5
2005	25SEP	27SEP	12.6	03OCT	05OCT	12.2	09OCT	11OCT	12.2			
2007	16SEP	18SEP	18.6	23SEP	25SEP	19.7						
2008	04SEP	06SEP	19.8									
2009	03OCT	05OCT	16.3									
2011	25SEP	27SEP	20.1									
2012	09OCT	11OCT	14.0									

Table 4. Date and approximate maximum of artificial pulse flows in Cowichan River, 1988-2012 (pers. comm., Ron Ptolemy, B.C. Min. Env., from Hop Wo, Nagtegaal and Carter 2005). No pulse flows in 2013-2014.

PARAM=Discharge (m3/s)

The CORR Procedure

2 Variables: LowerCowichan UpperCowichan

Simple Statistics

Variable	N	Mean	Std Dev	Median	Minimum	Maximum
LowerCowichan	1866	52.28820	54.95199	35.80000	2.60808	450.00000
UpperCowichan	2719	44.38797	41.06250	33.70000	0.42500	311.00000

Spearman Correlation Coefficients
Prob > |r| under H0: Rho=0
Number of Observations

	Lower Cowichan	Upper Cowichan
LowerCowichan	1.00000	0.99096
		<.0001
	1866	1782
UpperCowichan	0.99096	1.00000
	<.0001	
	1782	2719

Table 5. Cross-correlation of calibration data from upper and *Lower Cowichan River* daily mean discharge data (observed). Calibration data were sub-sampled from available discharge data by selecting the 10^{th}, 20^{th}, and 30^{th} observations of each month of the year for all years available, exclusive of pulse flow dates.

	Water Temperature						Percentiles			
	Dates	Min	Mean	Max	Std	Skew	P25	P50	P75	P95
Year										
2000	125	4.87	11.64	18.81	4.11	-0.00	8.0	12.2	15.2	17.8
2001	364	4.55	11.73	21.89	5.10	0.27	6.6	11.1	16.9	19.9
2002	365	4.75	11.86	22.59	5.38	0.34	6.8	10.7	16.9	20.7
2003	365	4.89	12.20	23.17	5.44	0.41	6.9	11.2	17.2	21.3
2004	366	4.01	12.75	23.33	5.55	0.24	7.6	12.2	17.0	22.2
2005	365	3.52	12.13	22.53	5.35	0.27	7.2	12.2	16.6	21.4
2006	364	4.86	11.90	23.82	5.38	0.42	6.7	11.1	16.8	20.4
2007	365	4.95	11.66	22.61	5.36	0.32	6.3	11.0	16.4	20.4
2008	366	3.49	11.33	21.94	5.36	0.26	6.1	10.7	16.2	20.2
2009	365	3.46	11.56	24.68	5.98	0.35	5.7	10.2	17.3	21.0
2010	365	5.26	11.72	21.85	5.12	0.43	6.7	11.3	16.1	20.9
2011	365	4.07	11.25	20.67	5.33	0.30	6.1	10.3	16.2	19.7
2012	346	4.43	11.60	22.02	5.28	0.29	6.2	11.5	15.9	20.6
All	4486	3.46	11.80	24.68	5.37	0.32	6.7	11.1	16.6	20.7

Table 6. Annual summary of daily mean water temperature data for *Lower Cowichan River* (Source: CATALYST PAPER (CROFTON)). MEAN is average of daily mean temperatures from datalogger readings for #DATES times per year. MIN and MAX are minimum and maximum of the daily mean temperatures (i.e., not observed extrema).

	Water Temperature						Percentiles			
	Dates	Min	Mean	Max	Std	Skew	P25	P50	P75	P95
Year										
2000	94	7.57	13.37	18.81	3.18	-0.17	11.5	13.1	16.3	17.9
2001	122	7.83	14.83	21.89	3.73	-0.09	11.5	15.7	17.8	20.5
2002	122	6.79	14.97	21.49	4.21	-0.13	10.6	15.6	18.7	21.0
2003	122	7.31	15.00	22.06	4.35	-0.19	11.7	15.5	19.0	21.3
2004	122	8.68	15.45	22.71	4.03	0.21	11.9	15.2	18.8	22.3
2005	122	7.44	15.23	22.53	4.34	0.09	11.9	14.4	19.1	22.0
2006	121	6.57	14.52	21.26	4.24	-0.06	11.2	14.5	18.9	20.3
2007	122	6.25	14.70	21.64	4.10	-0.22	11.2	14.5	18.3	20.4
2008	122	8.71	14.78	21.94	3.65	0.00	11.2	15.7	17.6	20.4
2009	122	8.07	14.59	23.74	4.27	0.10	11.3	13.5	18.6	20.9
2010	122	6.45	14.74	21.85	4.02	-0.24	12.2	14.9	17.3	20.9
2011	122	6.67	14.89	20.67	4.32	-0.41	11.3	15.2	19.1	20.2
2012	122	8.00	14.74	22.02	4.05	0.10	11.6	14.8	17.8	21.3
All	1557	6.25	14.78	23.74	4.07	-0.05	11.5	15.0	18.2	21.1

Table 7. Annual summary of daily mean water temperature data for *Lower Cowichan River* for migration period (August-November) (Source: CATALYST PAPER (Crofton)). Mean is average of daily mean temperatures from datalogger readings for #Dates times per year. Min and Max are minimum and maximum of the daily mean temperatures (i.e., not observed extrema).

	Calibration		Validation	
	Warming	Cooling	Warming	Cooling
	Observations	Observations	Observations	Observations
Year				
2000			0	88
2001			120	119
2002	121	119		
2003			121	119
2004	121	119		
2005			121	119
2006	121	118		
2007	121	119		
2008	121	119		
2009	121	119		
2010	121	119		
2011	121	119		
2012			121	119

Table 8. Number of annual water temperature observations available for *Lower Cowichan River* air/water temperature analyses, partitioned into warming and cooling seasons for seasonal relationships. Air/water temperature model calibration data years were selected based on strength of association between air and water time-series and range of temperature observations.

---------- Site=Cowichan Dataset=Calibration ----------

The NLIN Procedure

Source	DF	Sum of Squares	Mean Square	F Value	Approx Pr > F
Model	4	448051	112013	54520.0	<.0001
Error	1915	3934.4	2.0545		
Uncorrected Total	1919	451985			

Parameter	Estimate	Approx Std Error	Approximate 95% Confidence Limits	
alpha	24.9066	0.5283	23.8705	25.9426
beta	14.1438	0.2085	13.7350	14.5527
gamma	0.2286	0.0128	0.2034	0.2537
mu	6.4616	0.3365	5.8016	7.1216

Source	DF	Sum of Squares	Mean Square	F Value	Approx Pr > F
Model	3	19457.1	6485.7	4796.36	<.0001
Error	964	1303.5	1.3522		
Corrected Total	967	20760.6			

Parameter	Estimate	Approx Std Error	Approximate 95% Confidence Limits	
alpha	23.9995	0.4430	23.1302	24.8688
beta	13.3821	0.1639	13.0605	13.7037
gamma	0.2541	0.0147	0.2252	0.2830
mu	4.5913	0.4448	3.7183	5.4643

Source	DF	Sum of Squares	Mean Square	F Value	Approx Pr > F
Model	3	13983.0	4661.0	4687.92	<.0001
Error	947	941.6	0.9943		
Corrected Total	950	14924.6			

Parameter	Estimate	Approx Std Error	Approximate 95% Confidence Limits	
alpha	29.5264	1.7532	26.0857	32.9670
beta	14.1418	0.6660	12.8349	15.4488
gamma	0.1282	0.0141	0.1005	0.1559
mu	3.2687	1.0256	1.2559	5.2815

Obs	Season Numerator	Season Denominator	NSC Season Data	NSC All Data	NSC Season - NSC All	Result
1	2245.10	35685.19	0.93709	0.89123	0.045853	Hysteresis detected

Table 9. Logistic regression output for air/water temperature relationship between the *Shawnigan Lake* 7d-CMAT (air temperature index) and calibration data for *Lower Cowichan River* daily mean water temperatures: seasons combined (top); warming season (middle); cooling season (bottom).

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	19274	19274	12524.4	<.0001
Error	966	1486.59783	1.53892		
Corrected Total	967	20761			

Root MSE	1.24053	R-Square	0.9284
Dependent Mean	14.22048	Adj R-Sq	0.9283
Coeff Var	8.72356		

Parameter Estimates

Variable	Label	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	Intercept	1	0.49580	0.12896	3.84	0.0001
Shawnigan_7DMAT	7d-MAT	1	1.03210	0.00922	111.91	<.0001

Parameter Estimates

Variable	Label	DF	95% Confidence Limits	
Intercept	Intercept	1	0.24273	0.74887
Shawnigan_7DMAT	7d-MAT	1	1.01400	1.05020

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	13918	13918	13122.6	<.0001
Error	949	1006.52927	1.06062		
Corrected Total	950	14925			

Root MSE	1.02986	R-Square	0.9326
Dependent Mean	15.22868	Adj R-Sq	0.9325
Coeff Var	6.76266		

Parameter Estimates

Variable	Label	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	Intercept	1	5.44248	0.09172	59.34	<.0001
Shawnigan_7DMAT	7d-MAT	1	0.77758	0.00679	114.55	<.0001

Parameter Estimates

Variable	Label	DF	95% Confidence Limits	
Intercept	Intercept	1	5.26248	5.62249
Shawnigan_7DMAT	7d-MAT	1	0.76426	0.79090

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Shawnigan_7DMAT	1	32535.78233	32535.78233	19793.7	<.0001
Season	1	1285.58631	1285.58631	782.11	<.0001

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Shawnigan_7DMAT	1	6258.282837	6258.282837	4807.06	<.0001
Season	1	1305.839083	1305.839083	1003.03	<.0001
Shawnigan_7DM*Season	1	656.284133	656.284133	504.10	<.0001

Table 10. Linear regression output for air/water temperature relationship between the *Shawnigan Lake* 7d-CMAT (air temperature index) and calibration data for *Lower Cowichan River* daily mean water temperatures: warming season (top); cooling season (middle). Type III sum of squares for season effect and season interaction effect are highly significant (bottom), indicating that hysteresis exists and that seasonal models provide the best fit to the data.

---- Site=Cowichan Dataset=Validation Season=Warming ----

Pearson Correlation Coefficients, N = 483
Prob > |r| under H0: Rho=0

	Logistic Model Water Temp	Linear Model Water Temp
WaterT	0.95456	0.95309
Daily MWT	<.0001	<.0001

Spearman Correlation Coefficients, N = 483
Prob > |r| under H0: Rho=0

	Logistic Model Water Temp	Linear Model Water Temp
WaterT	0.95225	0.95225
Daily MWT	<.0001	<.0001

---- Site=Cowichan Dataset=Validation Season=Cooling ----

Pearson Correlation Coefficients, N = 564
Prob > |r| under H0: Rho=0

	Logistic Model Water Temp	Linear Model Water Temp
WaterT	0.96927	0.96629
Daily MWT	<.0001	<.0001

Spearman Correlation Coefficients, N = 564
Prob > |r| under H0: Rho=0

	Logistic Model Water Temp	Linear Model Water Temp
WaterT	0.96970	0.96970
Daily MWT	<.0001	<.0001

Table 11. Comparison of Pearson (least squares) and Spearman (rank) correlation coefficients for observed versus estimated (from logistic and linear models) daily mean water temperature for air/water temperature relationships for validation data years in the *Lower Cowichan River*: warming season (top); cooling season (bottom). Analysis indicates equal predictive power between the two model types.

Pulse Releases and Lower Cowichan Flows

	Count	Min Flow	Mean Flow	Max Flow	Min Mig%	Mean Mig%	Max Mig%
Flow Level							
Natural (<8 cms)	1188	2.6	5.3	8.0	0.0	0.6	13.1
Pulsed (<8 cms)	26	5.4	6.8	7.9	0.0	2.5	38.9
Natural (8-16 cms)	302	8.0	11.6	16.0	0.0	1.8	20.2
Pulsed (8-16 cms)	67	8.2	12.3	15.9	0.2	4.3	34.3
Natural (16-22 cms)	96	16.1	18.4	22.0	0.0	3.5	17.3
Pulsed (16-22 cms)	21	16.2	18.1	20.8	0.1	4.3	12.4
Natural (>22 cms)	782	22.1	79.1	407.0	0.0	0.3	39.0
Pulsed (>22 cms)	18	22.8	30.1	49.4	0.2	9.5	51.0
Total	2500	2.6	30.1	407.0	0.0	1.0	51.0

Table 12. Flow statistics (Count = number of migration dates) and Cowichan Chinook min, mean, and max daily migration rates partitioned by flow type (Natural vs Pulsed) and *Lower Cowichan River* discharge level.

	Water Temp											
	Low (<15C)				Mid (15-18C)				Top (>18C)			
	Count	Mean Flow	Mean Mig%	Max Mig%	Count	Mean Flow	Mean Mig%	Max Mig%	Count	Mean Flow	Mean Mig%	Max Mig%
Flow Level												
Natural (<8 cms)	225	5.6	1.4	12.4	452	5.3	0.7	13.1	511	5.3	0.2	6.1
Pulsed (<8 cms)	13	6.8	4.2	38.9	11	6.8	0.6	2.1	2	6.7	1.0	1.3
Natural (8-16 cms)	187	12.1	2.4	20.2	61	11.5	1.5	10.0	54	9.9	0.3	2.6
Pulsed (8-16 cms)	27	11.1	5.4	34.3	36	12.9	3.4	20.2	4	15.0	4.9	12.9
Natural (16-22 cms)	79	18.7	3.4	17.3	15	17.3	4.6	12.8	2	17.3	0.9	1.0
Pulsed (16-22 cms)	10	17.7	4.7	11.5	10	18.6	4.3	12.4	1	17.6	0.7	0.7
Natural (>22 cms)	760	78.7	0.3	39.0	15	98.0	0.4	2.2	7	73.3	0.0	0.0
Pulsed (>22 cms)	1	27.1	6.5	6.5	17	30.2	9.7	51.0				
Total	1302	50.3	1.2	39.0	617	9.8	1.3	51.0	581	6.6	0.2	12.9

Table 13. Flow statistics (Count = number of migration dates) and Cowichan Chinook min, mean, and max daily migration rates partitioned by flow type (Natural *versus* Pulsed) and *Lower Cowichan River* discharge and temperature levels.

Decadal Mean Monthly MWT Peaks > 17c

Site: Cowichan River

	Years in Decade	Mean No. Days			Mean Annual Total
		Sep	Oct	Nov	
Decade					
1910s	7	4.1			4.1
1920s	10	8.7			8.7
1930s	10	11.1	1.1		12.2
1940s	10	14.3	0.1		14.4
1950s	10	12.2	0.4		12.6
1960s	10	10.9			10.9
1970s	10	11.1			11.1
1980s	10	11.6	0.4		12.0
1990s	10	18.8	0.3		19.1
2000s	15	16.7	0.3		16.9

Annual Frequency & Mean Duration (days) for POT17c Events

	POT Event Duration (days)				
	N	Min	Avg	Max	Std
Decade					
1920s	31	1	22.4	86	23.7
1930s	42	1	16.3	75	19.4
1940s	35	1	22.1	77	22.7
1950s	34	1	20.9	77	19.6
1960s	39	1	18.3	90	20.6
1970s	38	0	18.2	79	23.1
1980s	37	1	19.9	71	23.0
1990s	38	2	24.5	94	28.9
2000s	53	1	25.6	97	31.6
Total	347	0	21.0	97	24.3

Table 14. Frequency analysis of decadal mean number of dates per month in which estimated mean water temperature in the *Lower Cowichan River* exceeded 17°C (top); min., mean and max. length (days) and total frequency of periods in which estimated mean water temperature continuously exceeded 17°C, by decade (bottom).

Decadal Mean Monthly Flow < 5 cms

Site: LowerCowichan River

	Years in Decade	Mean No. Days			Mean Annual Total
		Aug	Sep	Oct	
Decade					
1940s	4	14.8	21.3	6.5	42.5
1950s	10	11.5	20.0	4.8	36.3
1960s	10	5.2	5.4	1.6	12.2
1970s	10	5.4	1.9	1.5	8.8
1980s	10	9.6	5.6	5.4	20.6
1990s	10	9.8	8.1	0.7	18.6
2000s	15	9.1	8.3	3.7	21.0

Annual Frequency & Mean Duration (days) for POT < 5 cms Events

	POT Event Duration (days)				
	N	Min	Avg	Max	Std
Decade					
1940s	5	9	33.8	63	25.6
1950s	15	1	25.9	83	30.0
1960s	22	1	6.7	47	9.9
1970s	25	1	5.5	32	7.8
1980s	33	1	7.1	44	9.7
1990s	29	1	8.4	71	14.9
2000s	26	1	16.0	106	27.9
Total	155	1	11.2	106	19.1

Table 15. Frequency analysis of decadal mean number of dates per month in which observed or estimated daily discharge in the *Lower Cowichan River* did not exceed 5 cms (top); min., mean and max. length (days) and total frequency of periods in which observed or estimated daily discharge remained continuously below 5 cms, by decade (bottom).

FIGURES

Figure 1. Cowichan watershed, east coast of Vancouver Island, British Columbia (source: Wikipedia).

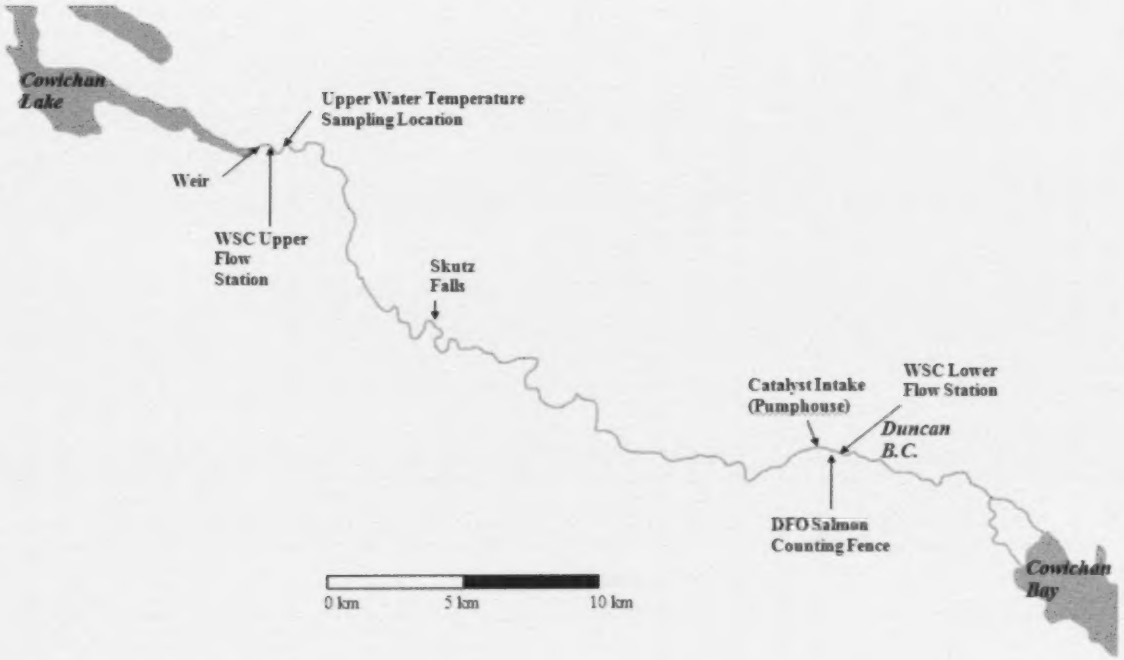


Figure 2. Cowichan watershed with key locations, ENVIRONMENT CANADA climate stations and CANADIAN HYDROGRAPHIC SURVEY water monitoring stations.

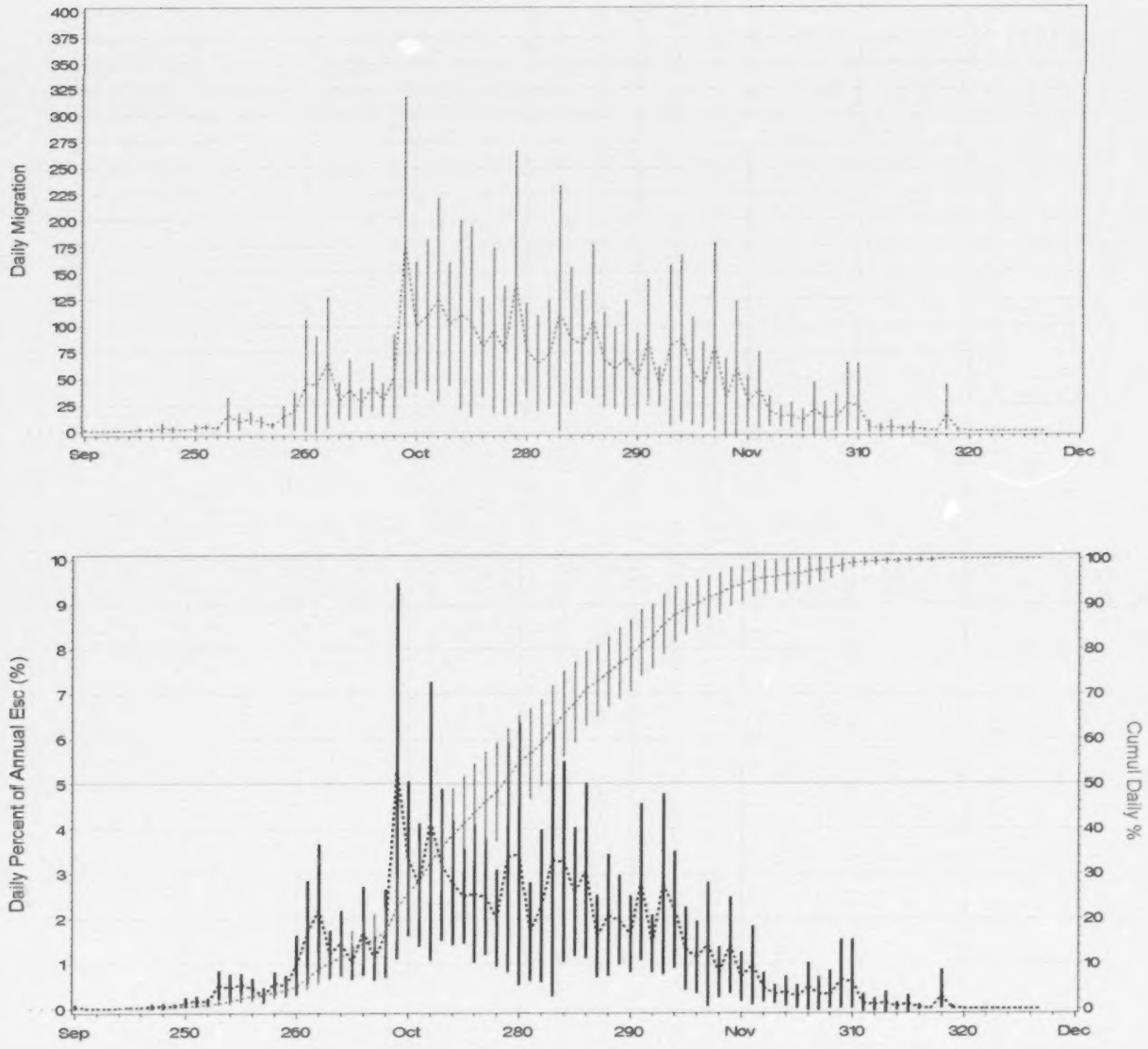


Figure 3. Historical migration timing (1988-2012, 2014). Mean daily and cumulative % of total annual escapement ± 2 standard errors of the mean (95% CI). Time-to-50% ~ day 279 ~ October 6th.

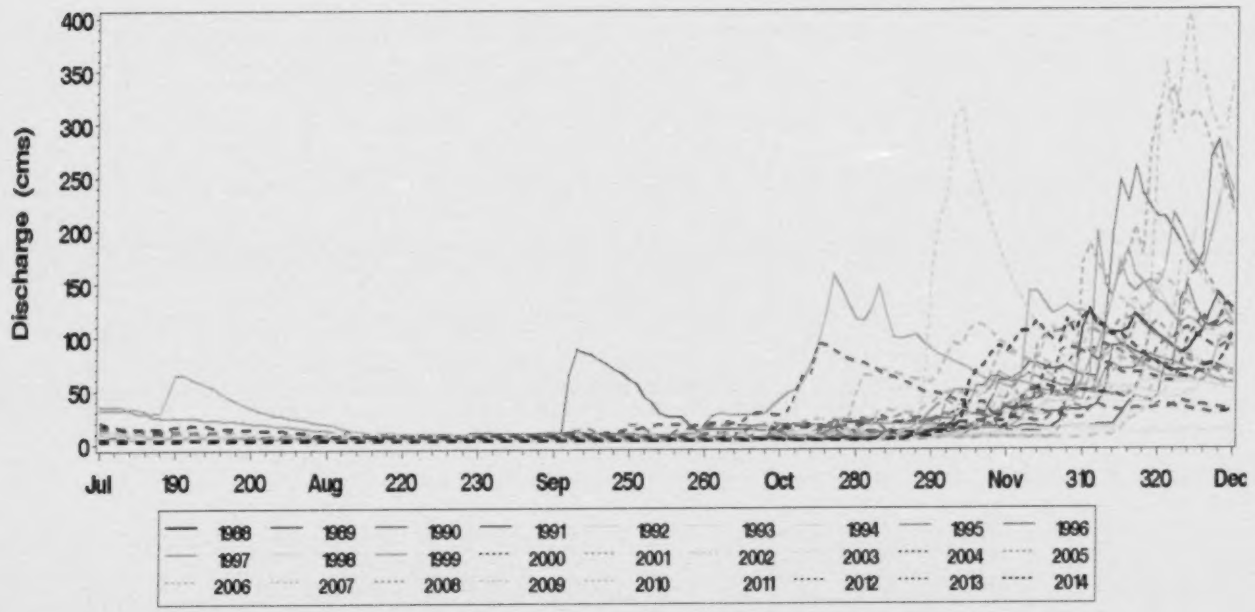


Figure 4. Observed annual daily mean discharge (cms) for the *Lower Cowichan River* (WSC Station 08HA011; 1988-2014).

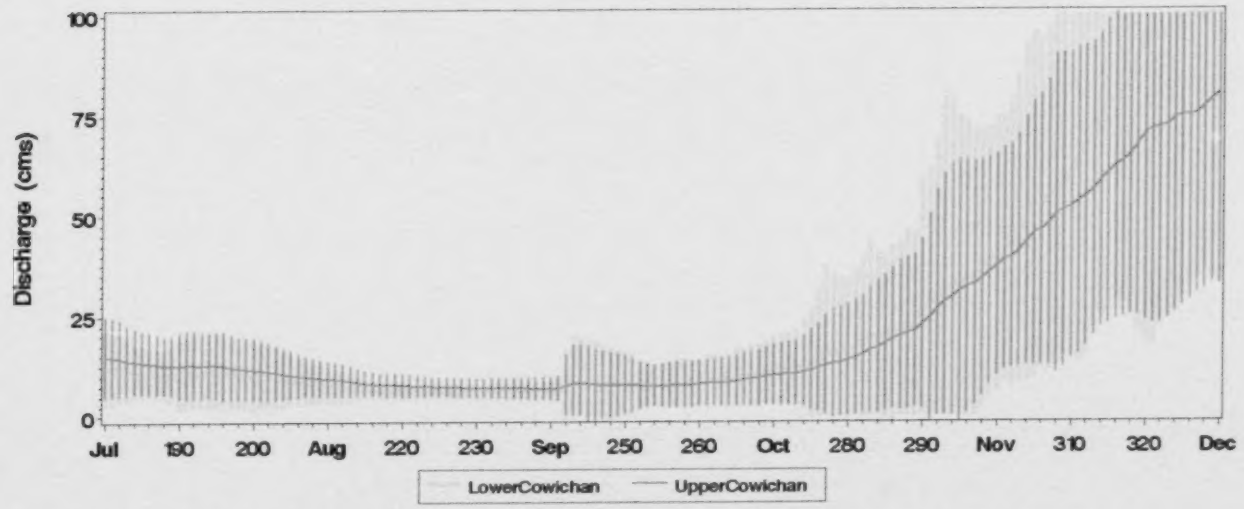


Figure 5. Observed daily mean discharge (cms) ± 1 standard deviation for the *Lower Cowichan River* (WSC Station 08HA011; 1960-2014) and *Upper Cowichan River* (WSC Station 08HA002; 1913-2011).

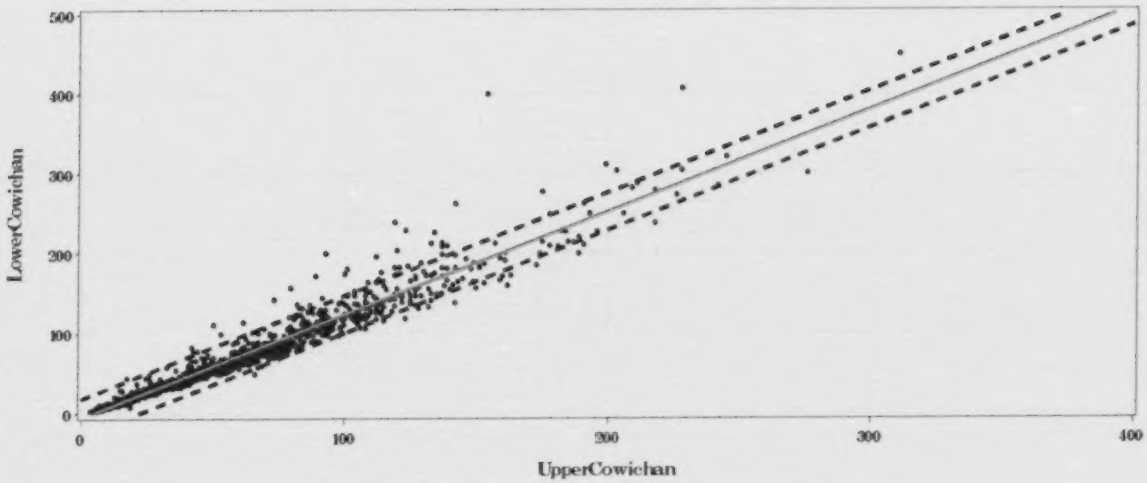


Figure 6. Daily mean discharge (cms) at the *Lower Cowichan River* (WSC Station 08HA011) as a linear function of *Upper Cowichan River* daily mean discharge (WSC Station 08HA022), based on calibration data (10th, 20th, and 30th observation sub-sampled from Jan-Dec data, exclusive of pulse flow dates).

Dependent Variable: LowerCowichan

Number of Observations Read	2719
Number of Observations Used	1782
Number of Observations with Missing Values	937

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	5181456	5181456	36795.7	<.0001
Error	1780	250654	140.81687		
Lack of Fit	917	152800	166.63074	1.47	<.0001
Pure Error	863	97854	113.38777		
Corrected Total	1781	5432110			

Root MSE	11.86663	R-Square	0.9539
Dependent Mean	52.36586	Adj R-Sq	0.9538
Coeff Var	22.66100		

Paraneter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	-5.16186	0.41105	-12.56	<.0001
UpperCowichan	1	1.28613	0.00670	191.82	<.0001

Figure 7. Regression statistics for the linear relationship (Y=a + bX) for daily mean discharge (cms) at the *Lower Cowichan River* as a function of function of *Upper Cowichan River* daily mean discharge (Figure 7). Lack of fit term is significant.

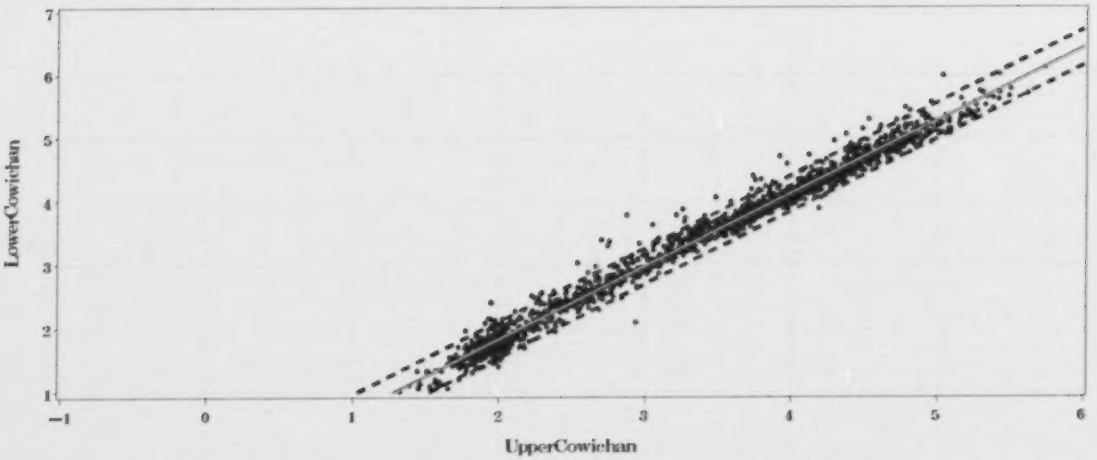


Figure 8. Daily mean discharge (cms) at the Lower *Cowichan River* (WSC Station 08HA011) as a logarithmic function of *Upper Cowichan River* daily mean discharge (WSC Station 08HA022), based on calibration data (10th, 20th, and 30th observation sub-sampled from Jan-Dec data, exclusive of pulse flow dates).

Dependent Variable: LowerCowichan

Number of Observations Read	2719
Number of Observations Used	1782
Number of Observations with Missing Values	937

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	1	2505.05744	2505.05744	127356	<.0001
Error	1780	35.01198	0.01967		
Lack of Fit	917	18.29028	0.01995	1.03	0.3332
Pure Error	863	16.72170	0.01938		
Corrected Total	1781	2540.06942			

Root MSE	0.14025	R-Square	0.9862
Dependent Mean	3.35152	Adj R-Sq	0.9862
Coeff Var	4.18462		

Parameter Estimates

Variable	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|
Intercept	1	-0.48247	0.01125	-42.90	<.0001
UpperCowichan	1	1.15175	0.00323	356.87	<.0001

Figure 9. Regression statistics for the log-log relationship ($Y = aX^b$) for daily mean discharge (cms) at the *Lower Cowichan River* as a function of *Upper Cowichan River* daily mean discharge (Figure 8). Lack of fit term is insignificant, indicating this is the most parsimonious model.

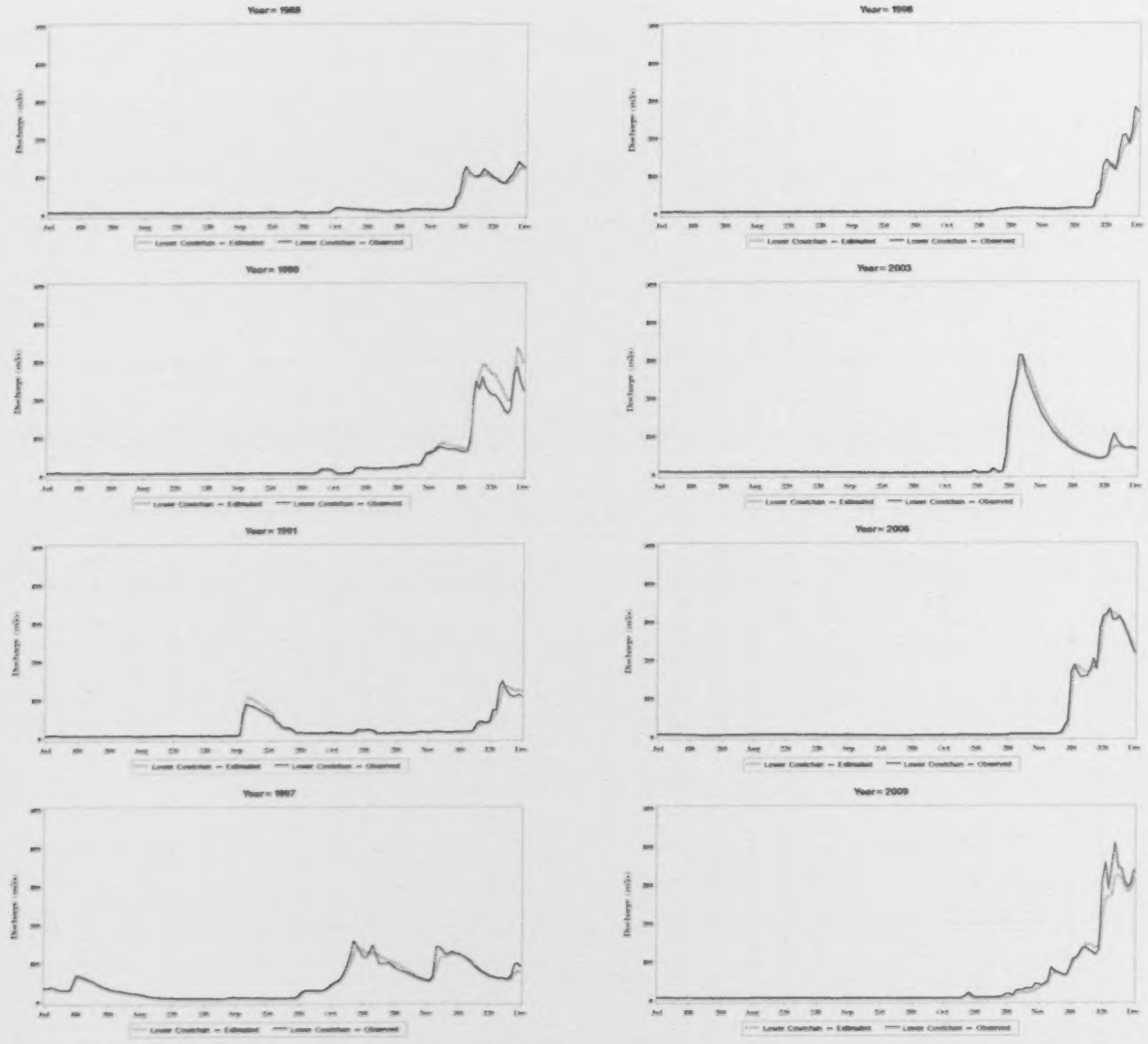


Figure 10. Observed (solid line) and estimated (red dashed line) daily mean discharge (cms) in the *Lower Cowichan River* (WSC Station 08HA011) for a subsample of years. Estimated Lower Cowichan discharge is derived from *Upper Cowichan River* daily mean discharge (WSC Station 08HA002) based on an exponential function ($Y = aX^b$; see Figure 8 and Figure 9). See also Table 4 for timing of annual artificial pulsed water releases from Lake Cowichan.

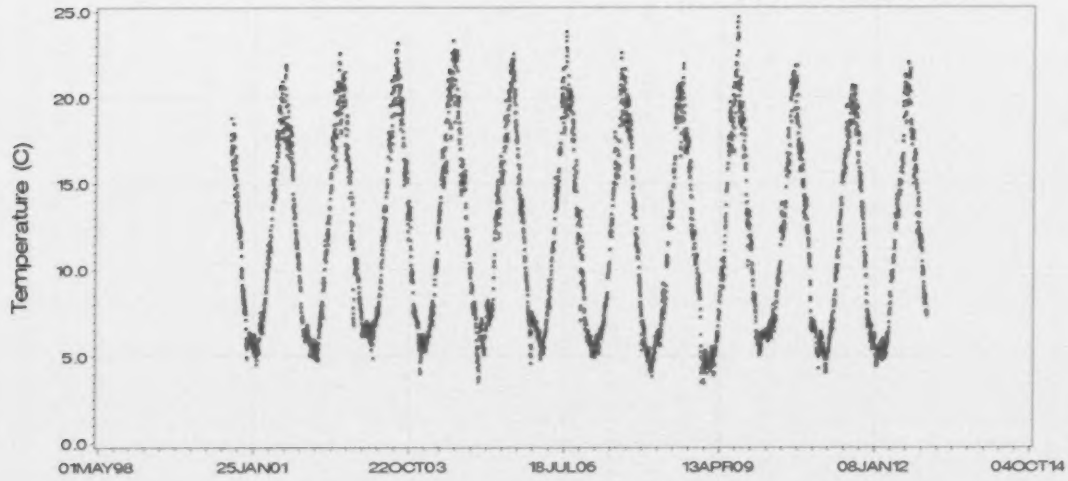


Figure 11. Water temperature data for *Lower Cowichan River* reference site at the Catalyst Paper Mill Pump-House, 2000-2012 (Source: CATALYST PAPER (CROFTON)).

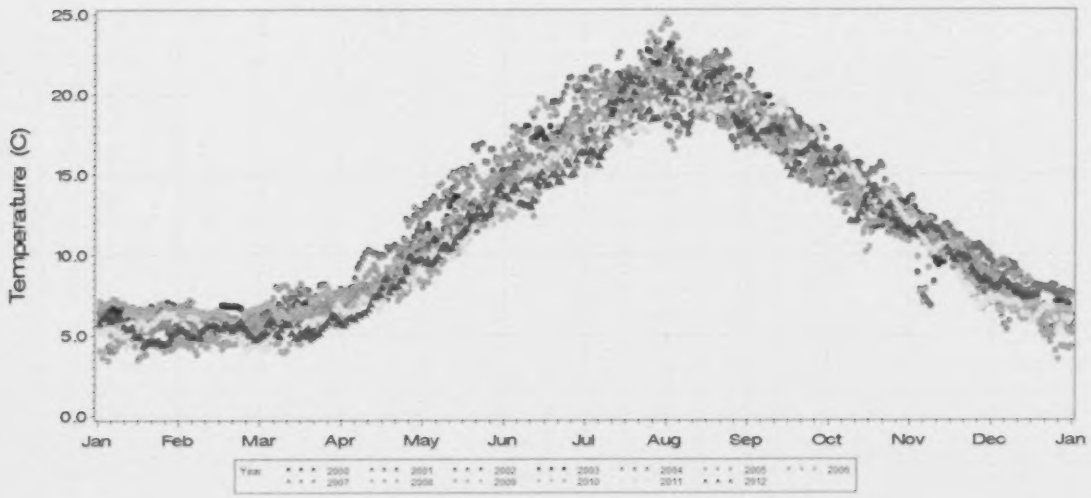


Figure 12. Annual thermograph of water temperature data for *Lower Cowichan River* reference site at the Catalyst Paper Mill Pump-House, 2000-2012 (Source: CATALYST PAPER (CROFTON)).

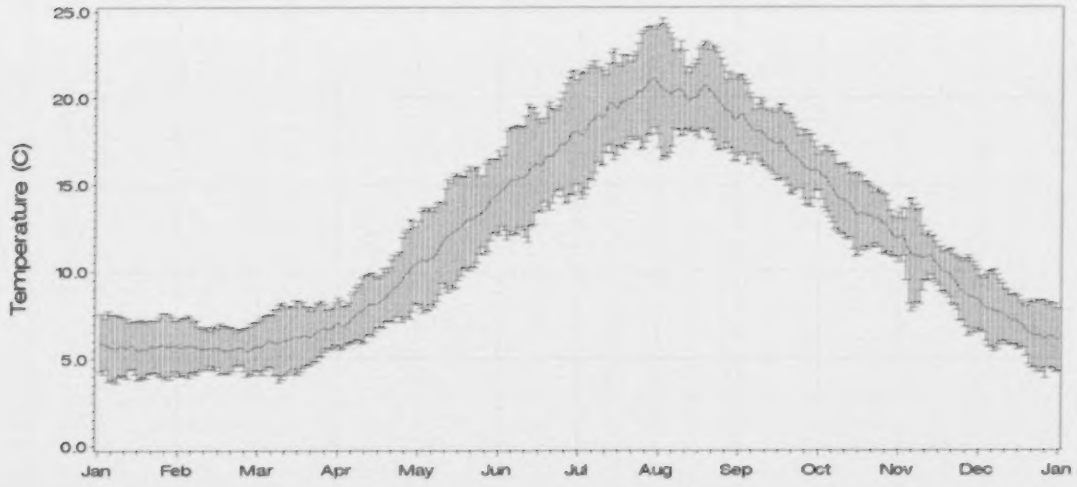


Figure 13. Annual thermograph of water temperature data ± two standard deviations for *Lower Cowichan River* reference site at the Catalyst Paper Mill Pump-House, 2000-2012 (Source: CATALYST PAPER (CROFTON)).

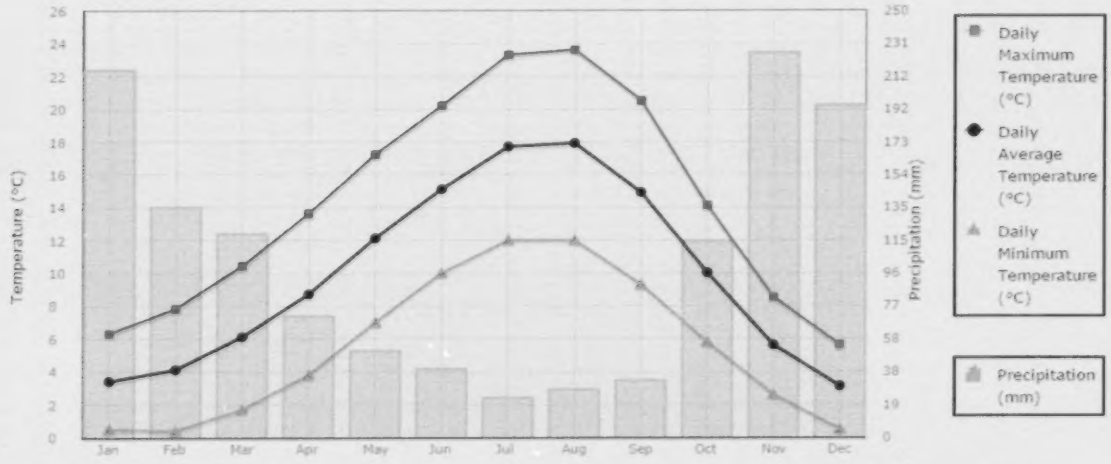


Figure 14. Air temperature and precipitation at *Shawnigan Lake*, 1981-2010 (Source: Environment Canada Climate Normals).

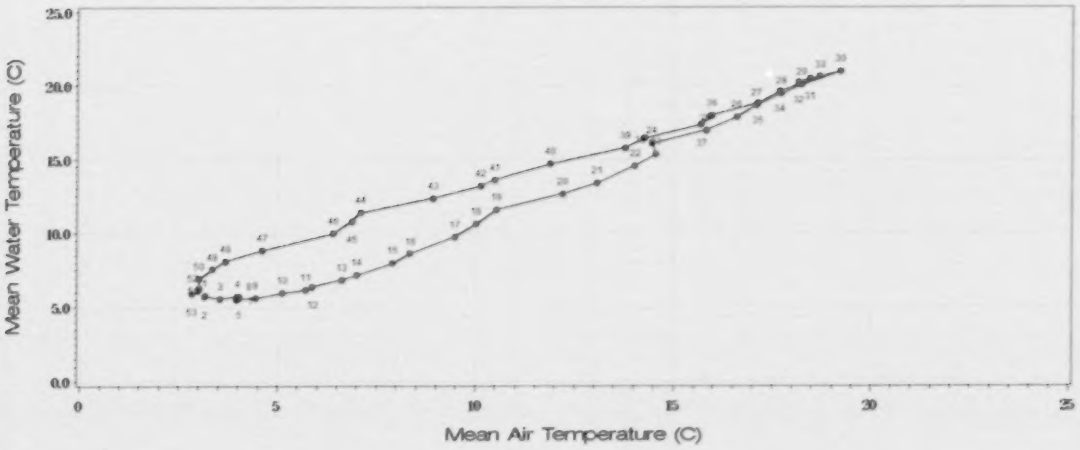


Figure 15. Derivation of seasonal turn-around point for *Lower Cowichan River*, based on maximum weekly mean air and water temperature data. The seasonal turn-around point is in week 30 or day 210, approx July 29th. The "warming season" therefore extends from April 1 to July 29th, followed by the "cooling season" from day 211-329, i.e., July 30th – November 25th.

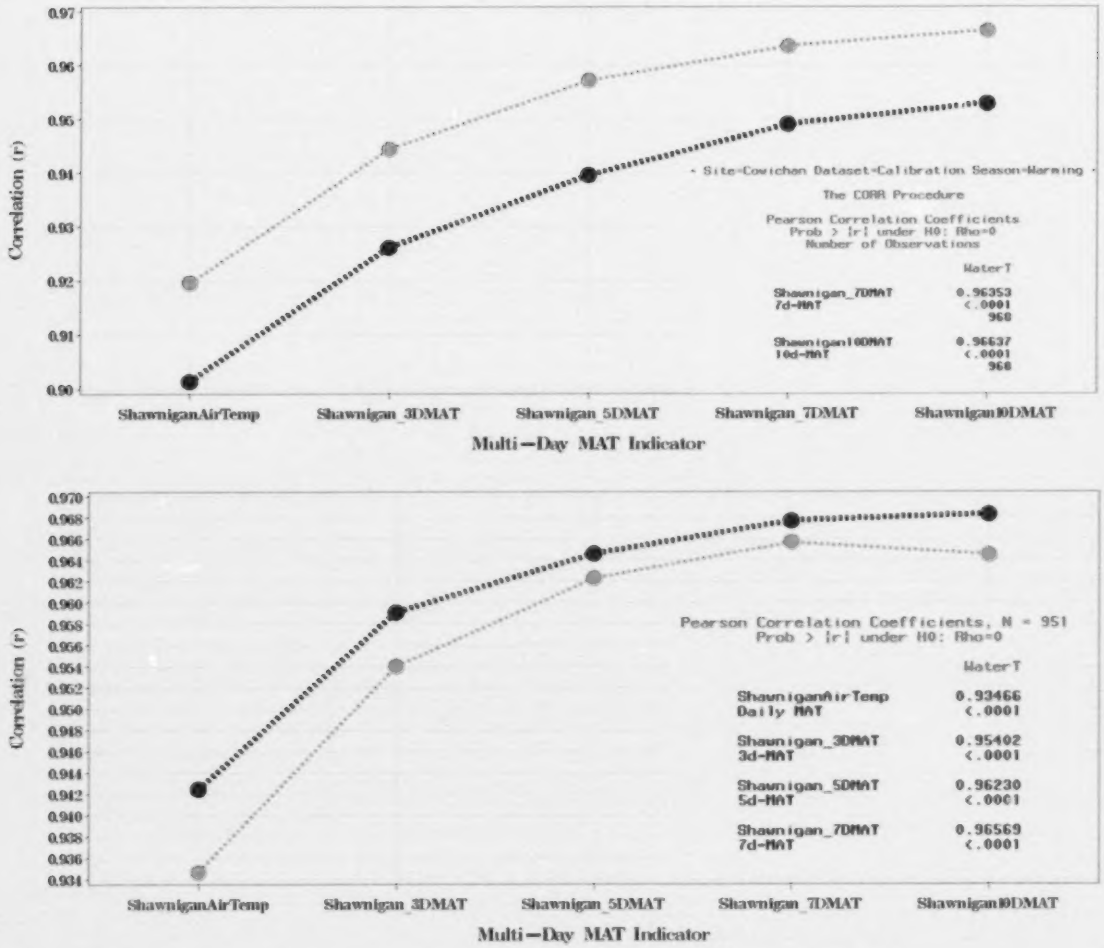


Figure 16. Derivation of optimum regional air temperature index for air/water temperature analyses, based on maximum all-year correlation between various *Shawnigan Lake* multi-day mean air temperature indicators (MATs) with *Lower Cowichan* daily mean water temperature (MWT) for calibration (red) and validation (black) data; warming season (top), cooling season (bottom). *Shawnigan Lake* air temperature indicators include (l-r): Air Temp (same day mean); 3-day centered moving average air temperature (3D-MAT), 5D-MAT, 7D-MAT, and 10-DMAT. Overall, the 7D-MAT provides the best trade-off between correlation and multi-day averaging (which affects predictive power at longer period lengths).

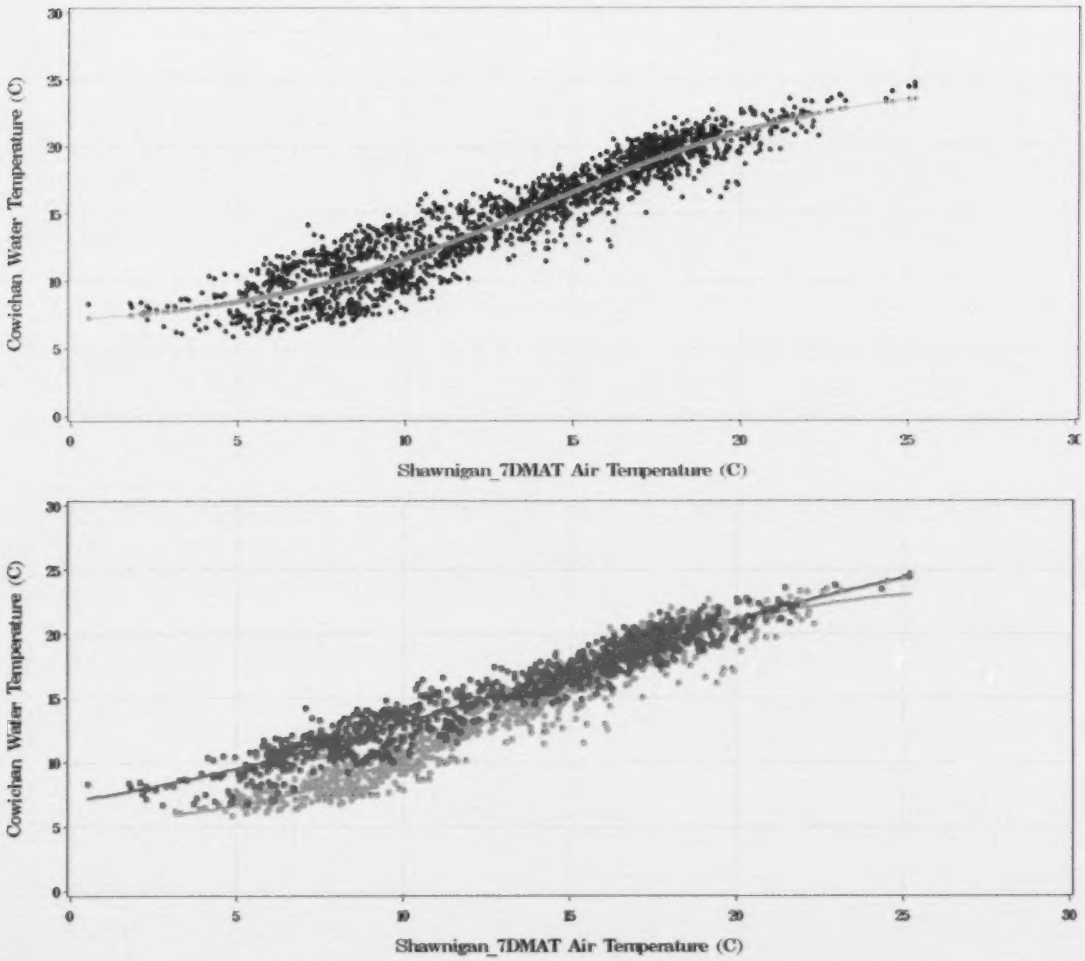

Cowichan Water Temperature (C)
Shawnigan_7DMAT Air Temperature (C)
Cowichan Water Temperature (C)
Shawnigan_7DMAT Air Temperature (C)

Figure 17. Logistic regression fits for air/water temperature relationship for Lower *Cowichan* daily mean water temperatures as a function of the *Shawnigan Lake* 7d-CMAT (air temperature index): seasons combined (top); separate warming season (red) and cooling seasons (blue)(bottom).

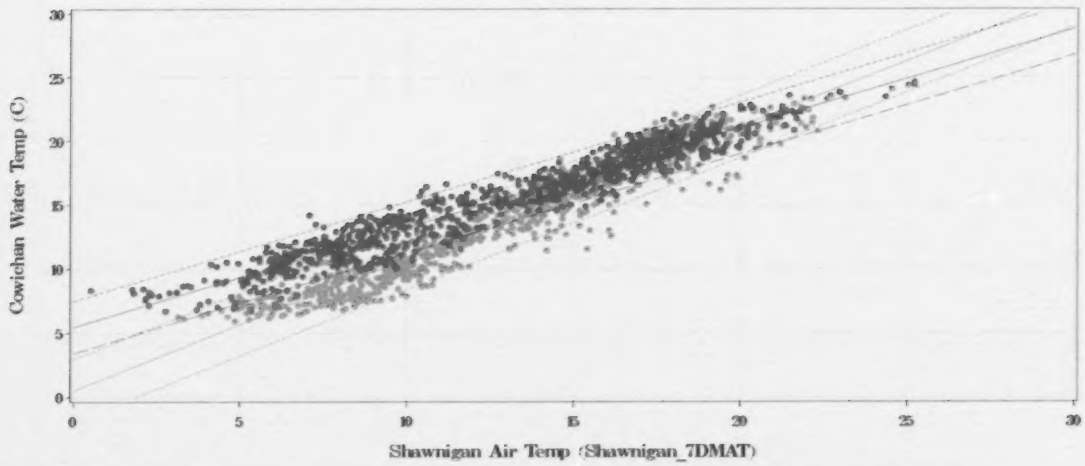


Figure 18. Linear regression fits for air/water temperature relationship for *Lower Cowichan River* daily mean water temperatures as a function of the *Shawnigan Lake* 7d-CMAT (air temperature index), by season (warming season (red) and cooling season (blue)).

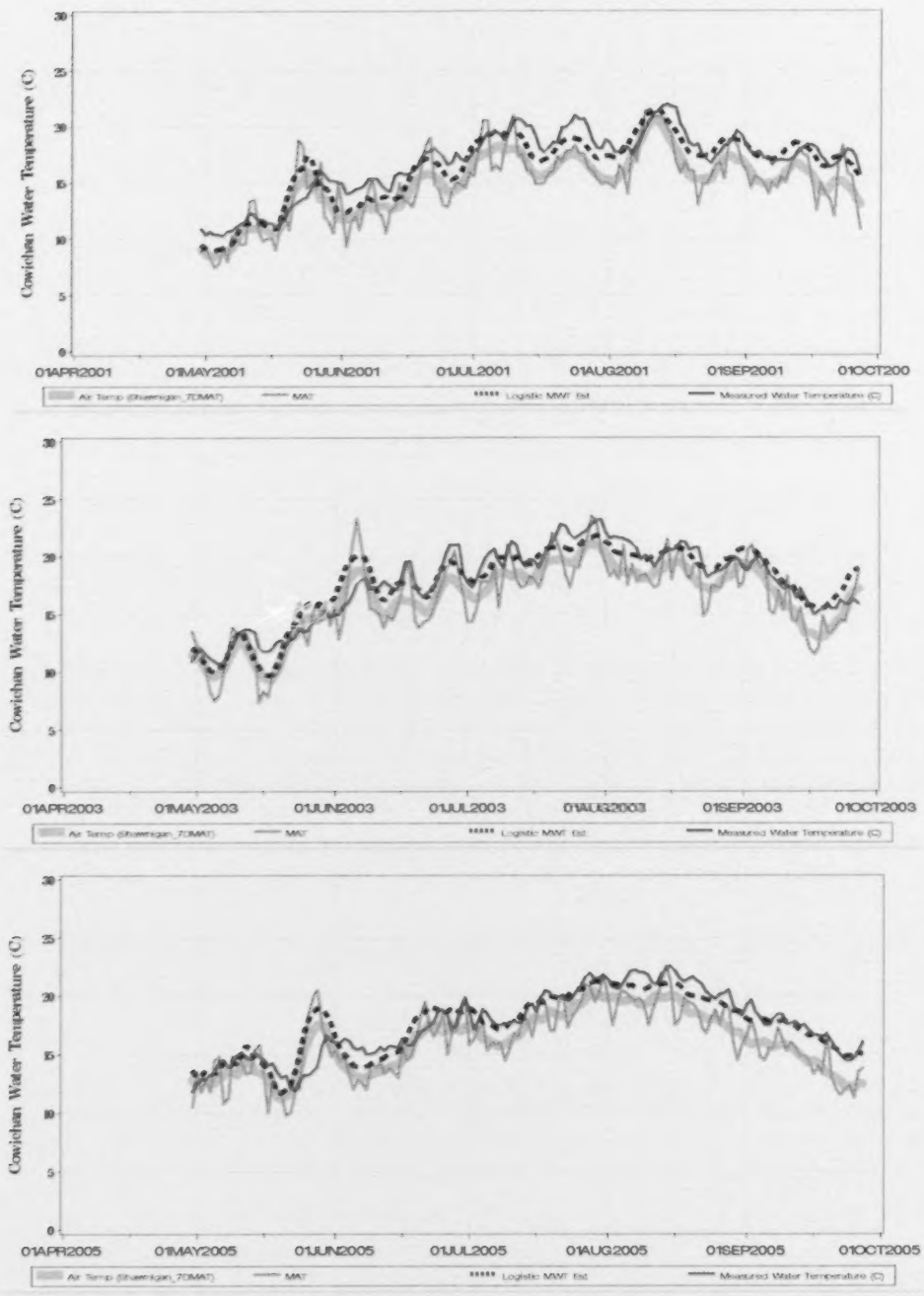


Figure 19. Sample validation plots of daily mean air temperature (red line), 7-day MAT index (broad pink line), and observed (blue solid line) and estimated (black dashed line, based on seasonal logistic regression models) daily mean water temperature for *Lower Cowichan River*, May-Oct 2001 (top), 2003 (middle), 2005 (bottom).

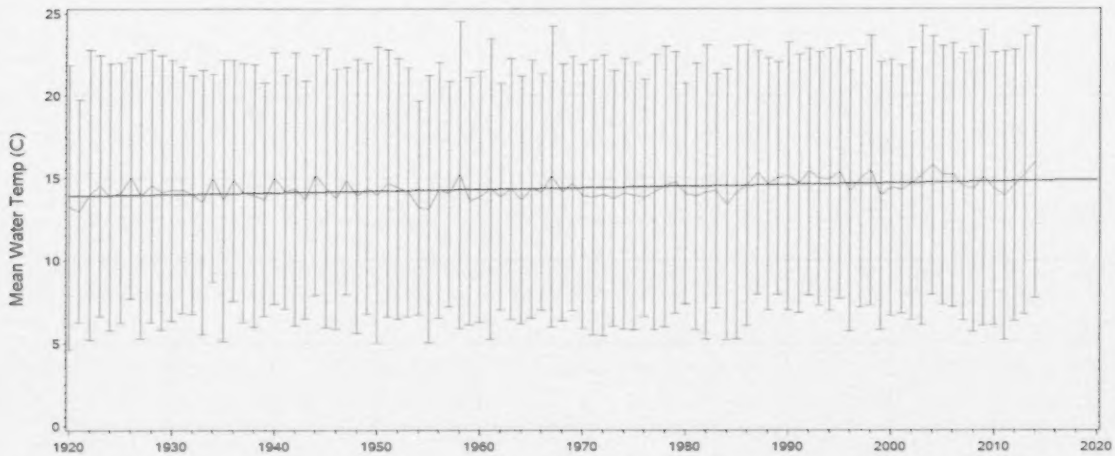


Figure 20. *Lower Cowichan River* mean water temperature ± 2 std deviations, August-November 1920-2012, based on seasonal logistic air/water temperature regression models. Trend: MWT = -4.70 + 0.0097 * Year (r^2 = 0.004; P < .0001).

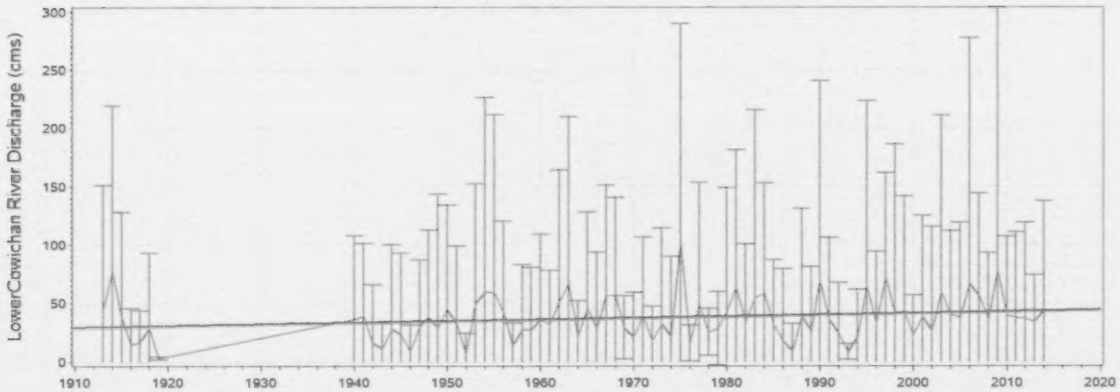


Figure 21. *Lower Cowichan River* mean discharge ± 2 std deviations, August-November. Observed (1960-2012), and estimated based on *Upper Cowichan River* discharge (1913-1959). Trend: Discharge = -231.8 + 0.136 * Year; r^2 = 0.005; P < .0001).

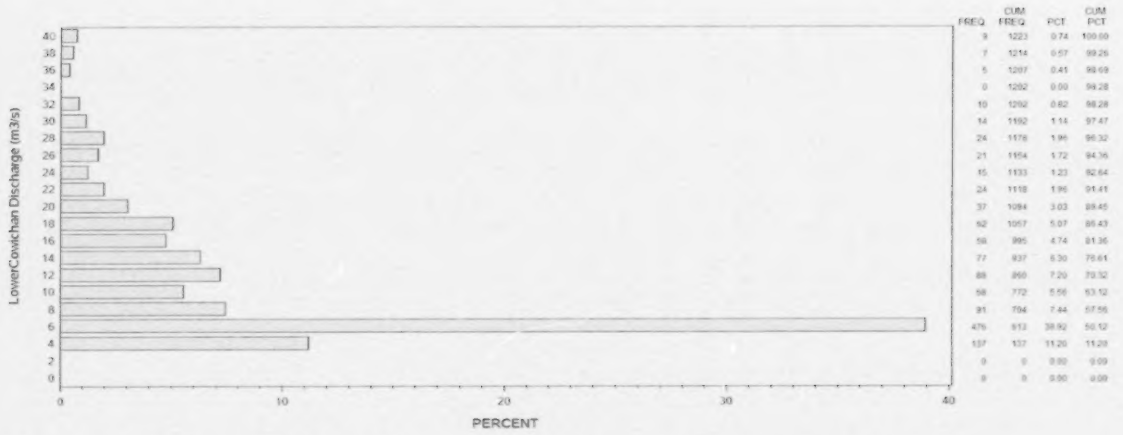


Figure 22. Frequency plot of historical Cowichan Chinook non-zero migration (unweighted tally of non-zero migration dates), at varying levels of *Lower Cowichan River* discharge. Most dates of migration occur at 5-7 cms.

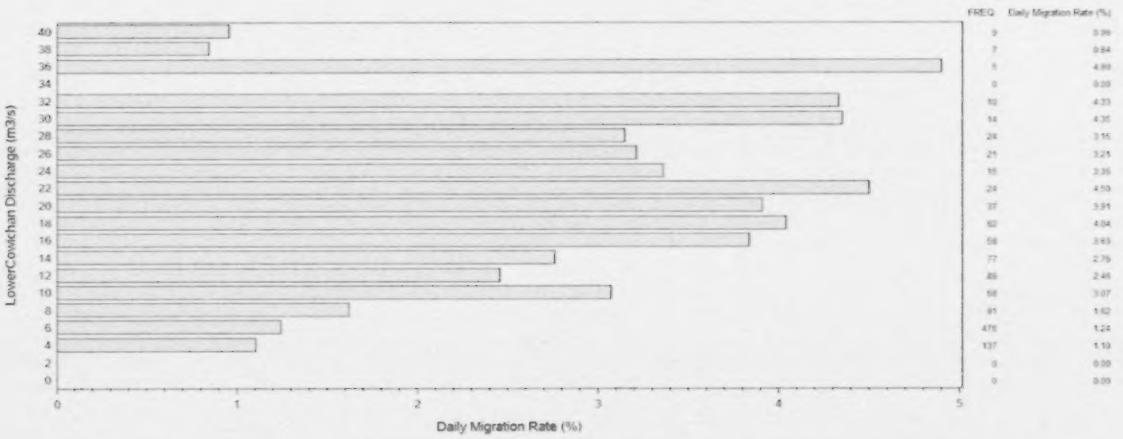


Figure 23. Frequency plot of historical Cowichan Chinook non-zero migration dates (weighted by daily migration rate), at varying levels of *Lower Cowichan River* discharge. Though most dates of migration occur at 5-7 cms (Figure 22), the highest daily migration rates (>3% per day) occur at 10-30 cms.

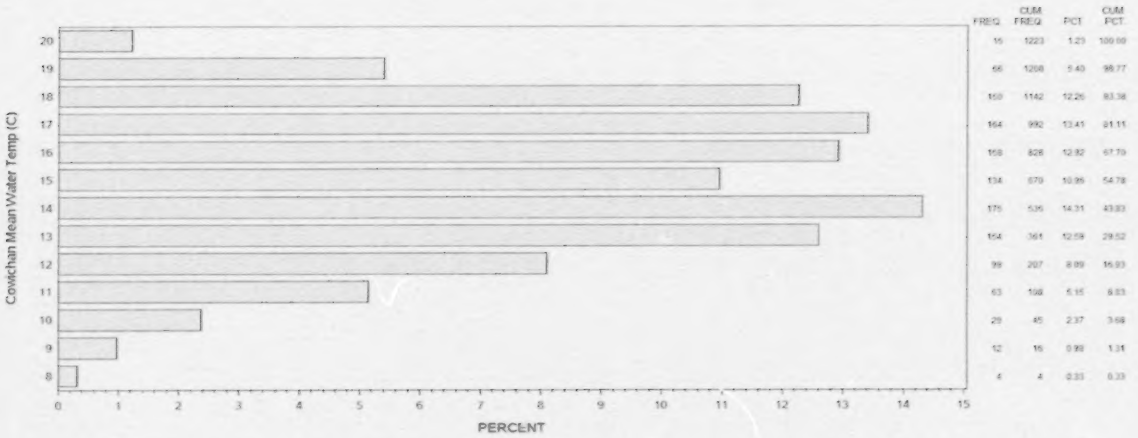


Figure 24. Frequency plot of historical Cowichan Chinook migration (unweighted tally of non-zero migration dates), at varying levels of *Lower Cowichan River* water temperature. Migration occurs at a wide range of temperatures, with ~75% at 13-18°C.

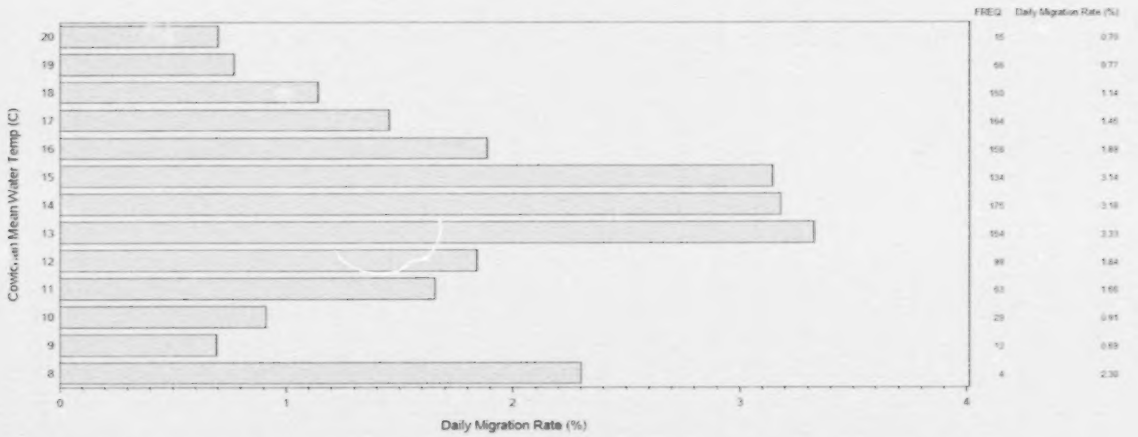


Figure 25. Frequency plot of historical Cowichan Chinook non-zero migration dates (weighted by daily migration rate), at varying levels of *Lower Cowichan River* water temperature. Though most dates of migration occur at 13-18°C (Figure 24), the highest migration rates occur at occur at 13-15°C.

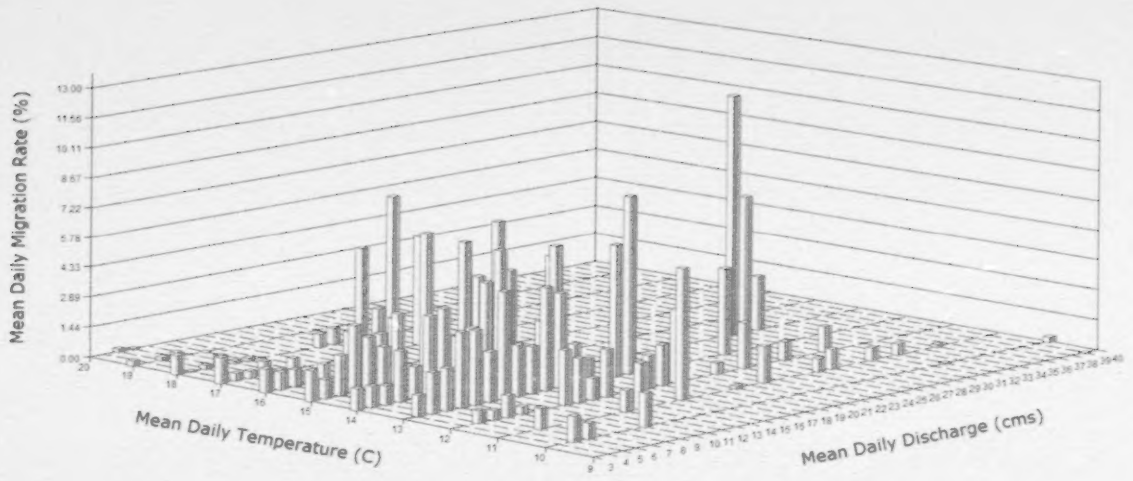


Figure 26. Frequency plot of historical Cowichan Chinook migration dates, weighted by the daily migration rate, at varying levels of *Lower Cowichan River* water temperature and discharge.

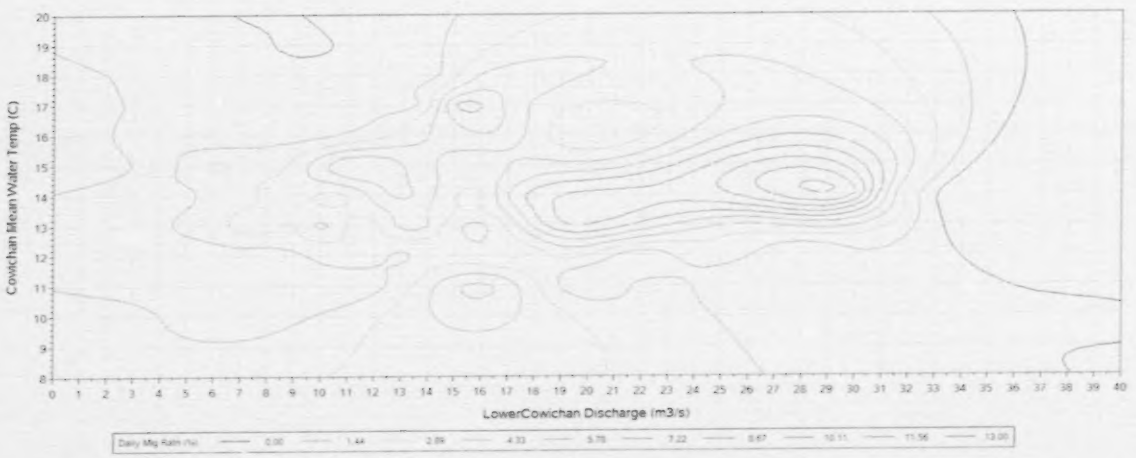


Figure 27. Smoothed contour plot of historical Cowichan Chinook daily migration frequency (weighted by the daily migration rate (% of annual escapement)), at varying levels of *Lower Cowichan River* water temperature and discharge.

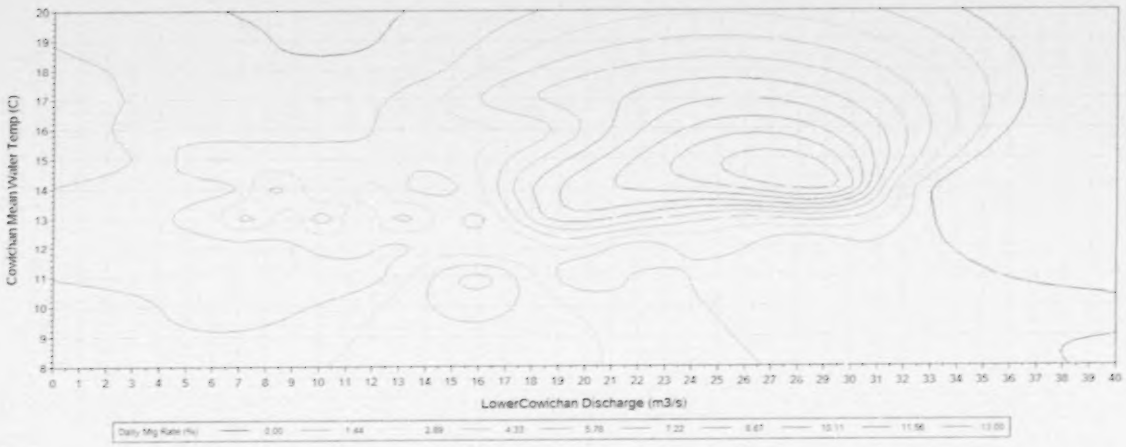


Figure 28. Cowichan Chinook daily migration rate (as in Figure 27), omitting pulse flow dates.

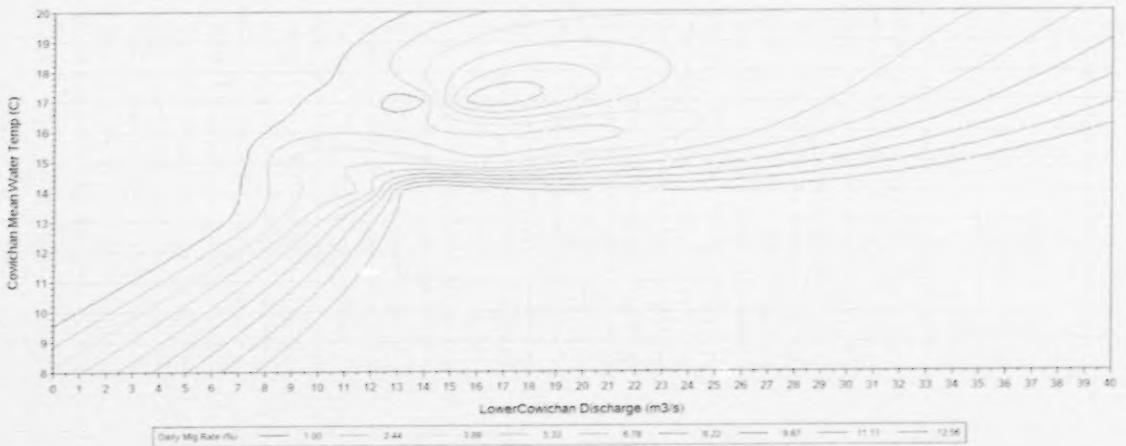


Figure 29. Cowichan Chinook daily migration rate (as in Figure 27), for pulse flow dates only. (Ignore graph portions below 15°C or above 22 cms due to insufficient data.)

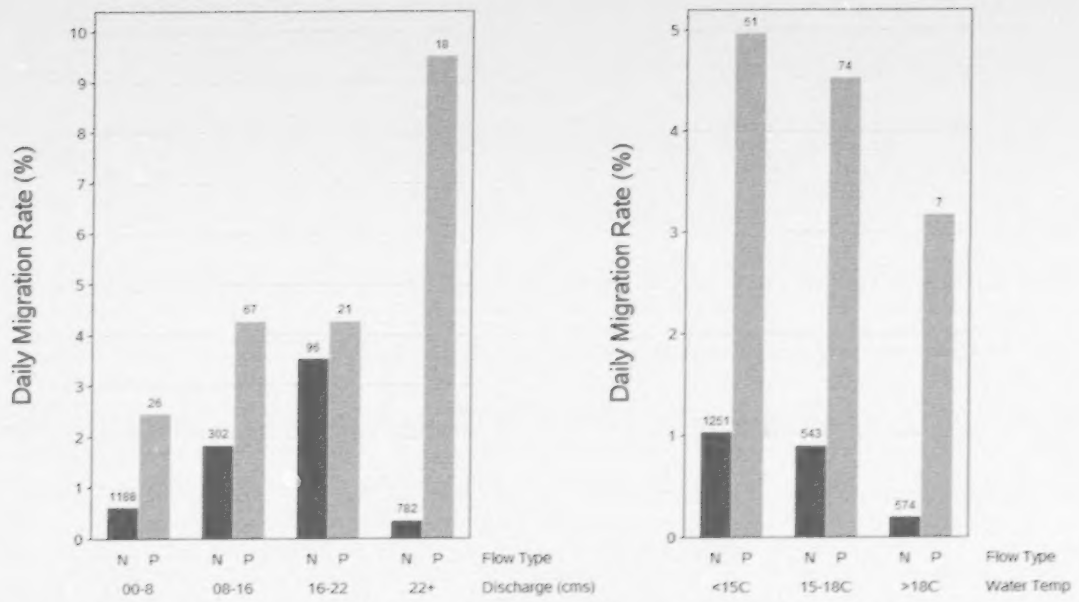


Figure 30. Cowichan Chinook mean daily migration rates partitioned by flow type (N=Natural vs P=Pulsed), at varying levels of *Lower Cowichan River* discharge (left) and water temperature (right).

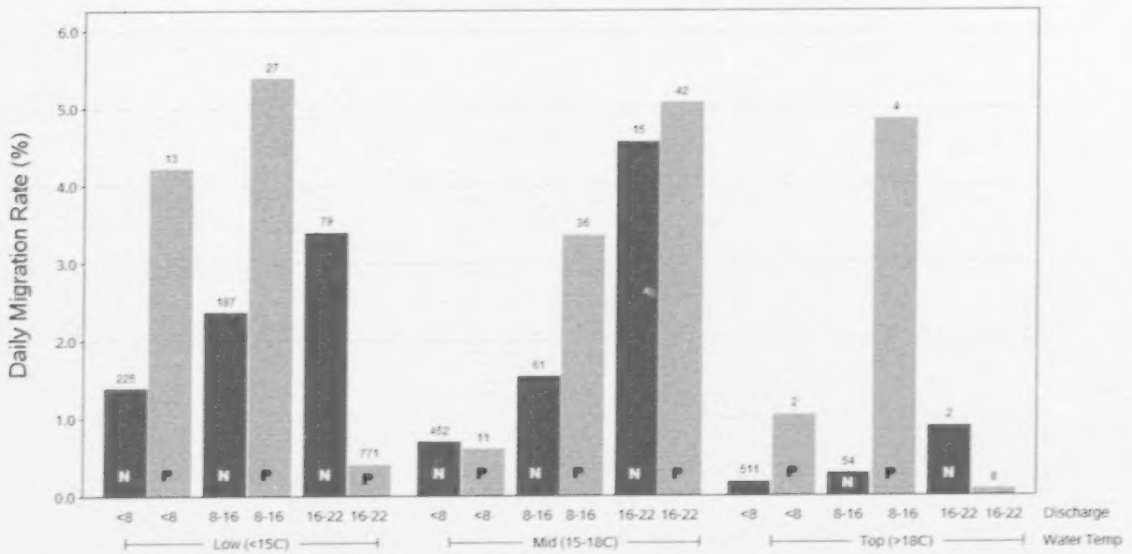


Figure 31. Cowichan Chinook mean daily migration rates partitioned by flow type (N=Natural vs P=Pulsed), grouped by *Lower Cowichan River* water temperature category and sub-grouped by discharge level.

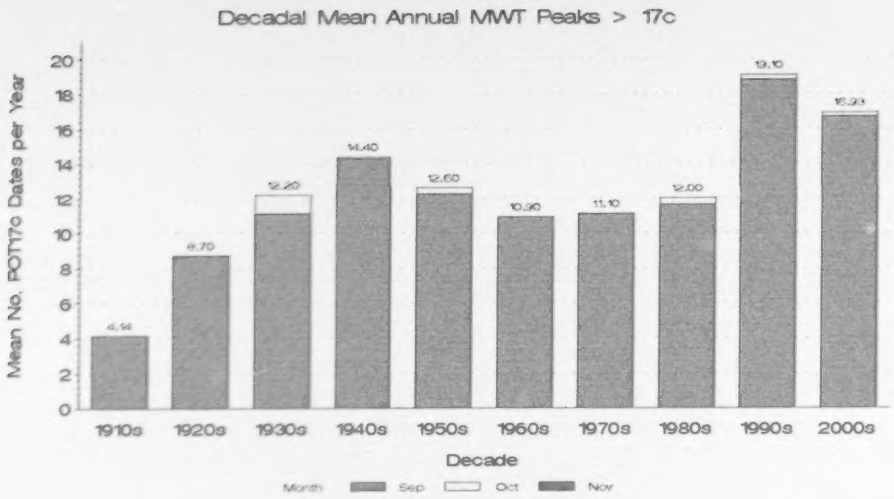


Figure 32. Frequency analysis of decadal mean number of dates per summer month in which mean water temperature (estimated) in the *Lower Cowichan River* exceeded 17°C. Cumulative number of $POT_{>17°C}$ dates per year has increased since the 1970s, to a total of about 17-19 days per year, mainly in September.

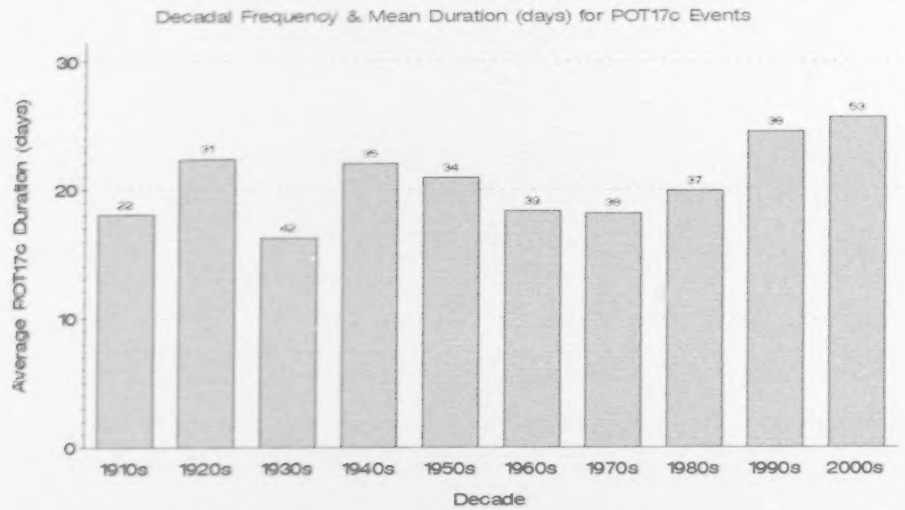


Figure 33. Mean length (days) and mean frequency of number of periods in which mean water temperature (estimated) in the *Lower Cowichan River* continuously exceeded 17°C, by decade. Average length of $POT_{>17°C}$ events has increased from an average of ~18 days in the 1960s-1970s to ~25 days in the 2000s, concurrent with an increase in the decadal total frequency of $POT_{>17°C}$ periods of that length from less than 37-39 to 53.

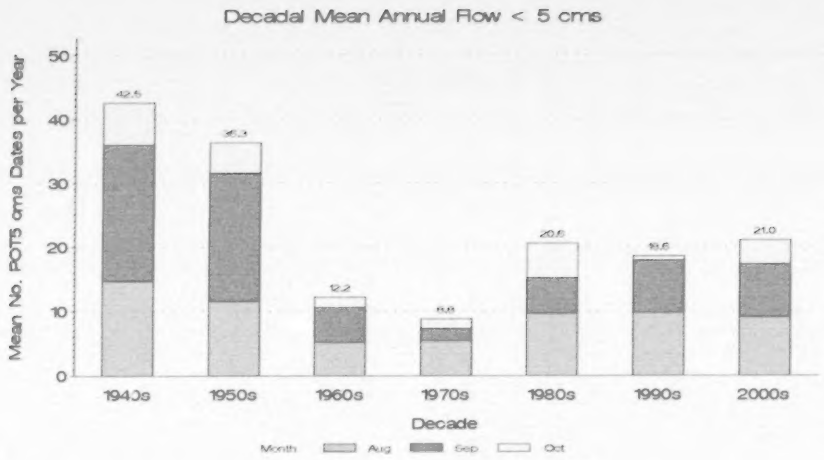


Figure 34. Frequency analysis of decadal mean number of "low flow" dates per month in the *Lower Cowichan River* (i.e., mean flow (observed + estimated) < 5 cms). Cumulative average dates per year (July-November period) shows beneficial effect of weir installation in the 1950s, with decreased frequency of low flow events in the 1960s and 1970s. However, the number of low flow events has increased to approximately 20 per year since the 1980s, mostly in August and September. Note: no discharge data available for the 1920s and 1930s.

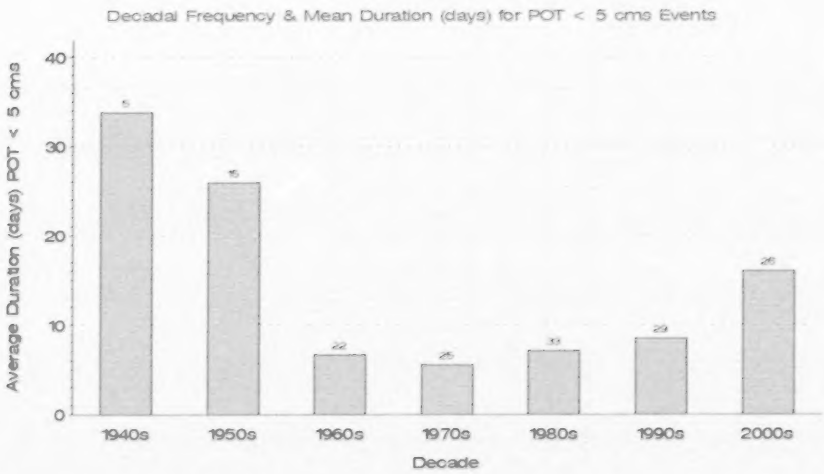
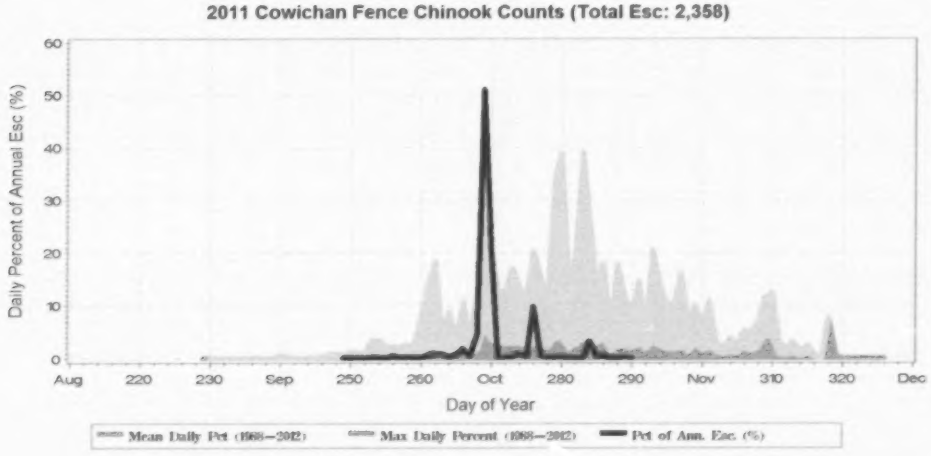


Figure 35. Mean length (days) and frequency of "low flow" periods in which *Lower Cowichan* discharge (observed + estimated) continuously remained below 5 cms, by decade. Average length of $POT_{<5cms}$ events reached a historic low in the 1970s (7.1 ± 9.7 days per event for 25 low flow periods in the decade) but has increased to 13.1 ± 22.8 days per period in the 2000s (based on 22 low flow periods in the decade). Note: no discharge data available for the 1920s and 1930s.

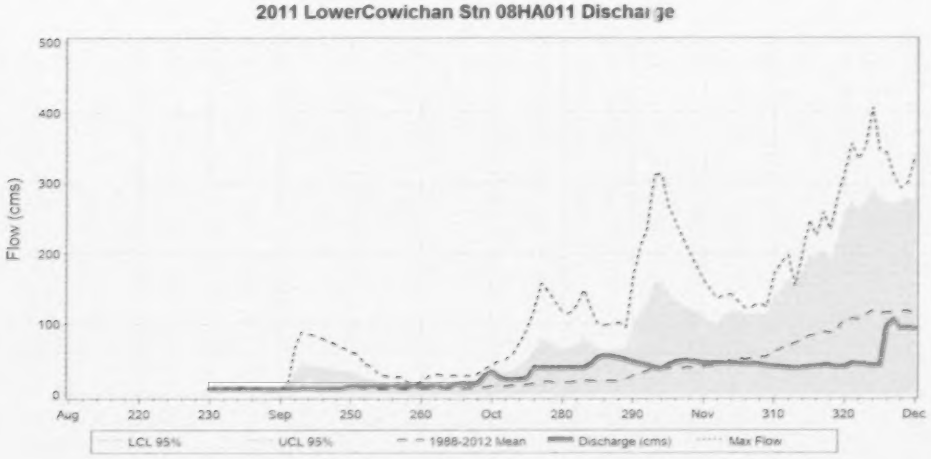
APPENDICES

Appendix A. Multi-panel plots of daily Cowichan Chinook migration in relation to environmental variables, by year, 1988-2012.

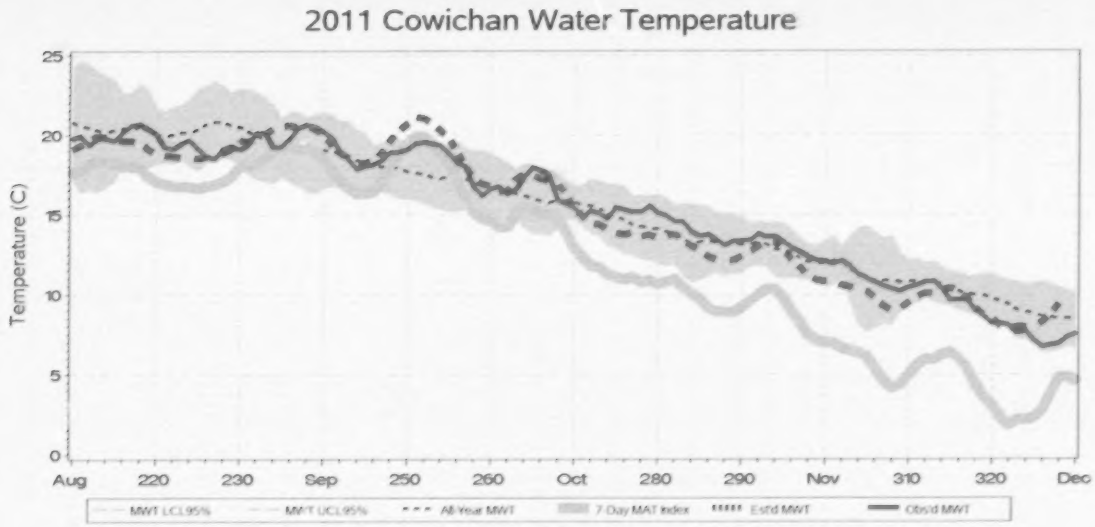
Sample plots for the year 2011 (below) display legend with vertical axis variates and horizontal axis with day of year (month label is *approximate* start of each month). Annual plots (following pages) are organized in a multi-panel format for comparison of the following variates:



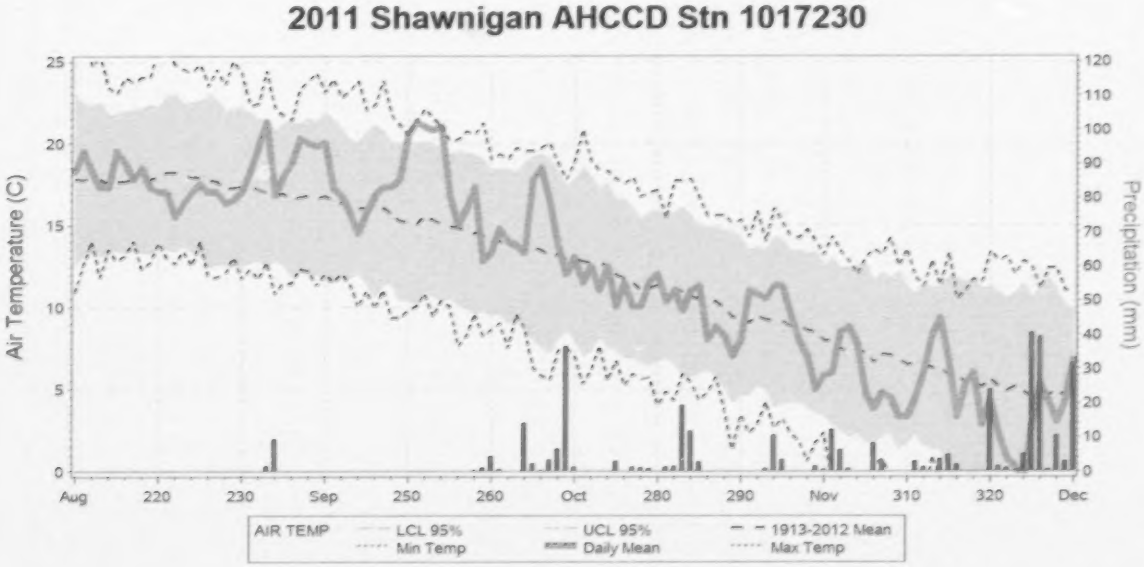
1. Daily migration rates as a percent (%) of annual stock escapement (black line), from daily sockeye (adult + jack) migrants counted at the Lake Cowichan weir. Historical mean daily migration rate (dark gray area) and maximum daily migration rate (light gray area) for years 1988-2012.



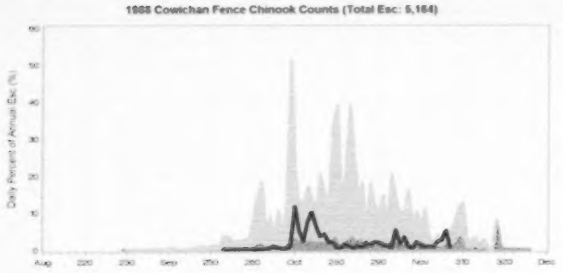
2. Daily mean discharge (cms) at WSC station *Lower Cowichan* (green line), with historical daily mean and variance (dashed line and green area), 1960-2012.

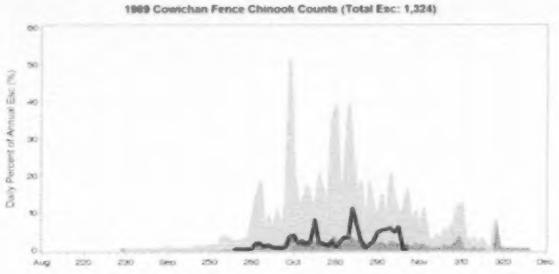


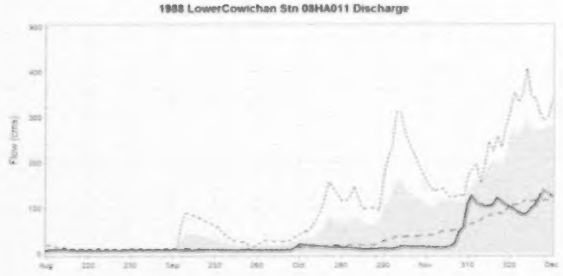
3. Observed (solid blue line) and estimated (dashed blue line) daily mean water temperature in the *Lower Cowichan*, with historical daily MWT and variance (dashed gray line and gray area), 1988-2012; daily air temperature index (pink).

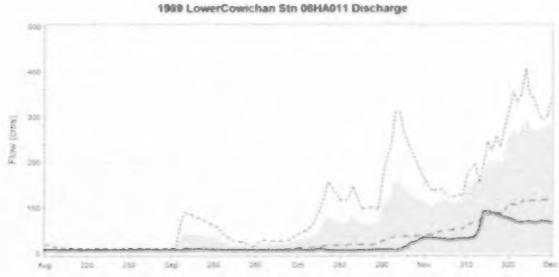


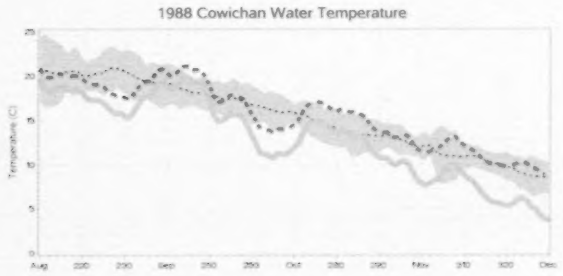
4. Precipitation (mm, blue bars) and daily mean air temperature (°C, red line) at EC meteorological station *Shawnigan Lake*, with historical daily mean and variance (dashed line and red area), 1911-2012.

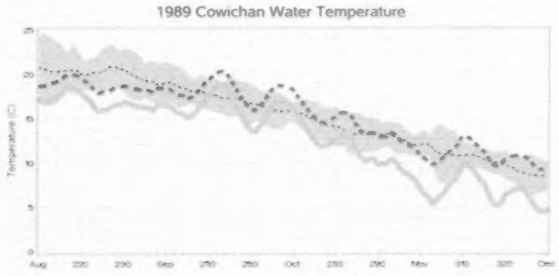


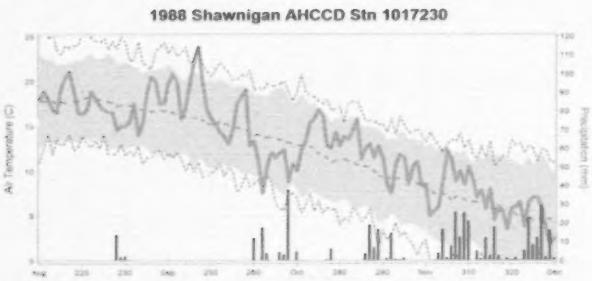


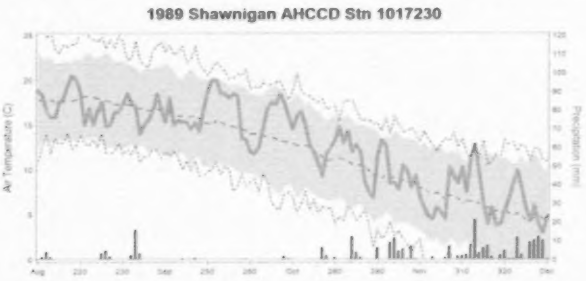


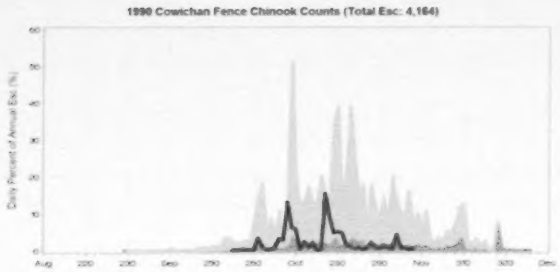


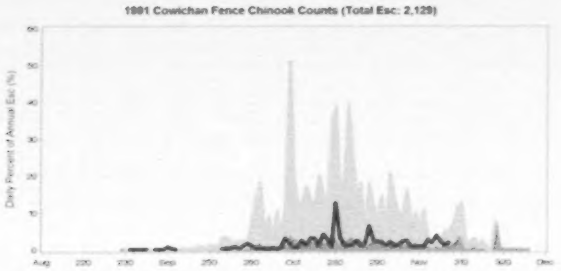


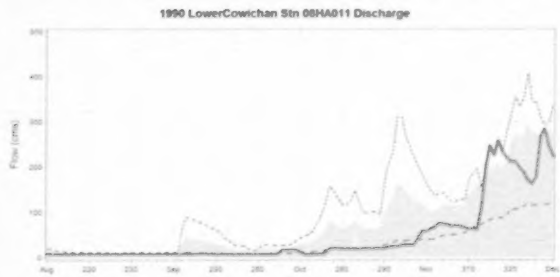


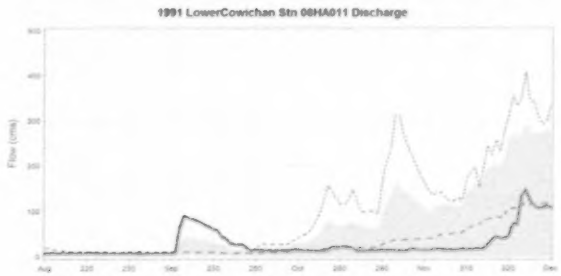


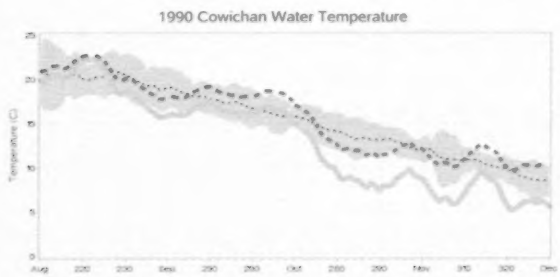


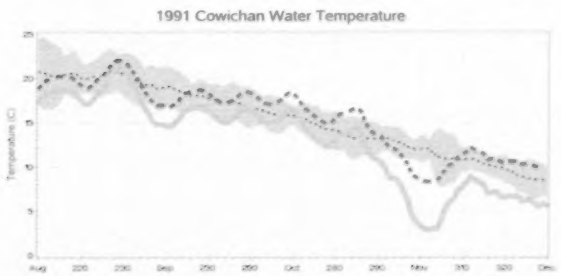

1990 Cowichan Fence Chinook Counts (Total Esc: 4,164)
Daily Percent of Annual Esc (%)

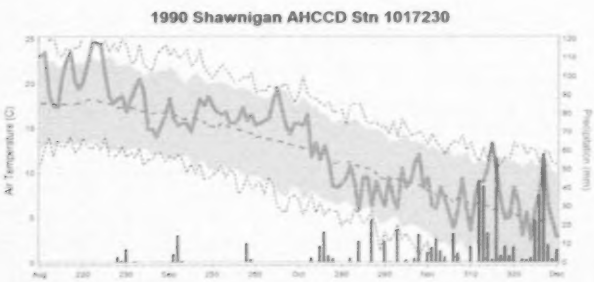

1991 Cowichan Fence Chinook Counts (Total Esc: 2,129)
Daily Percent of Annual Esc (%)

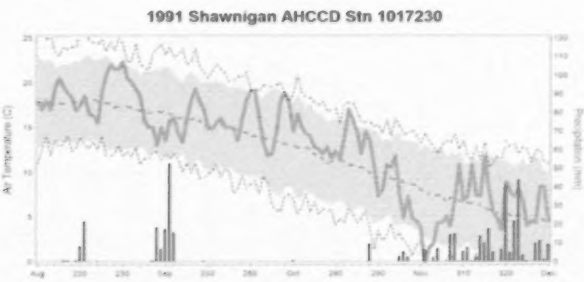

1990 LowerCowichan Stn 08HA011 Discharge
Flow (cms)

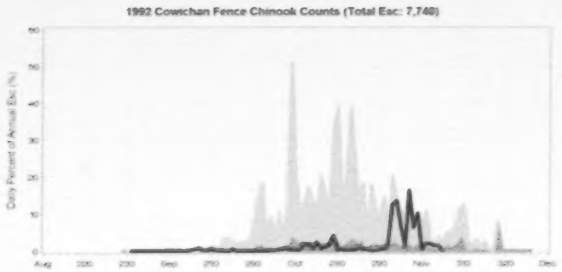

1991 LowerCowichan Stn 08HA011 Discharge
Flow (cms)

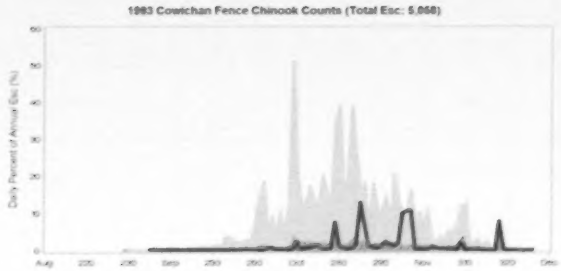

1990 Cowichan Water Temperature
Temperature (C)


1991 Cowichan Water Temperature
Temperature (C)

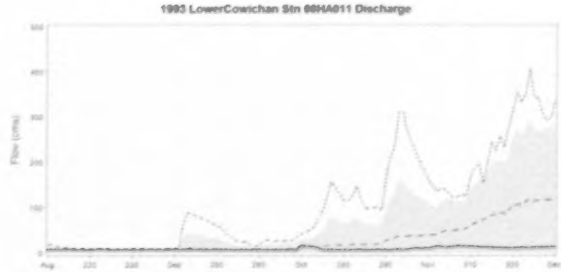

1990 Shawnigan AHCCD Stn 1017230
Air Temperature (C)
Precipitation (mm)

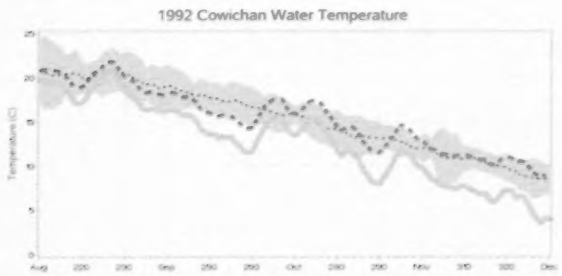

1991 Shawnigan AHCCD Stn 1017230
Air Temperature (C)
Precipitation (mm)

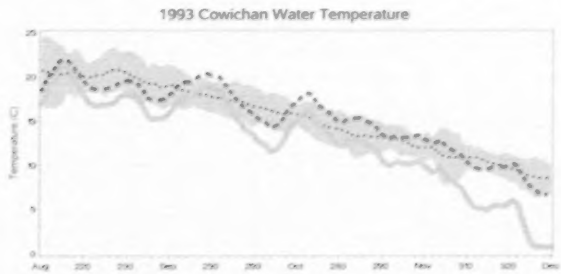

1992 Cowichan Fence Chinook Counts (Total Esc: 7,740)
Daily Percent of Annual Esc (%)

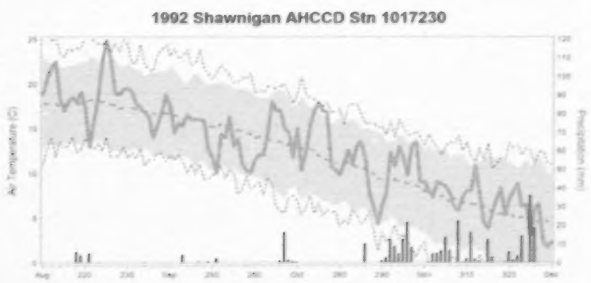

1993 Cowichan Fence Chinook Counts (Total Esc: 5,068)
Daily Percent of Annual Esc (%)

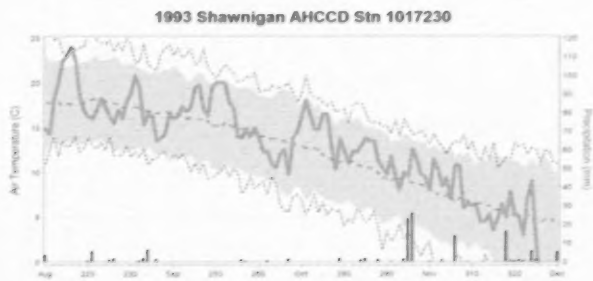
1992 LowerCowichan Stn 08HA011 Discharge
Flow (cms)

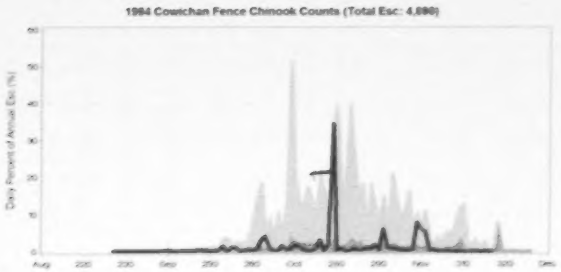

1993 LowerCowichan Stn 08HA011 Discharge
Flow (cms)

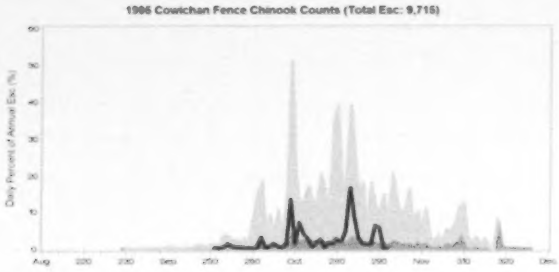

1992 Cowichan Water Temperature
Temperature (C)

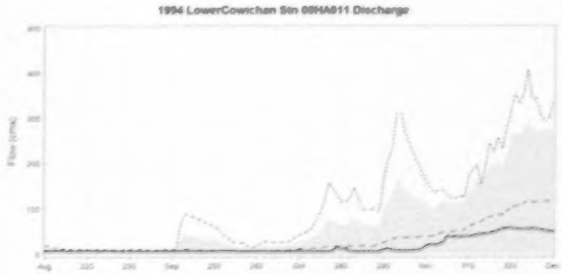

1993 Cowichan Water Temperature
Temperature (C)

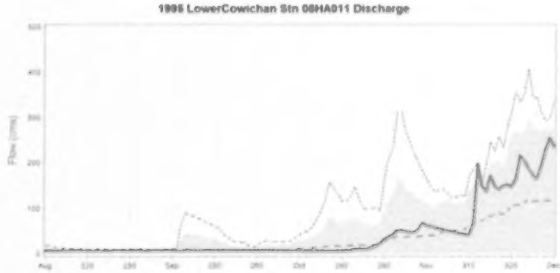

1992 Shawnigan AHCCD Stn 1017230
Air Temperature (C)

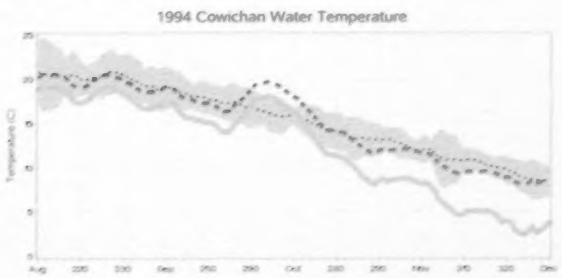

1993 Shawnigan AHCCD Stn 1017230
Air Temperature (C)

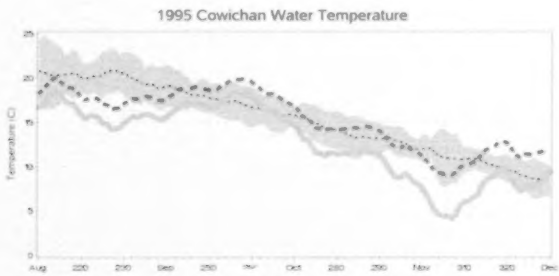

1994 Cowichan Fence Chinook Counts (Total Esc: 4,890)
Daily Percent of Annual Esc (%)


1995 Cowichan Fence Chinook Counts (Total Esc: 9,715)
Daily Percent of Annual Esc (%)

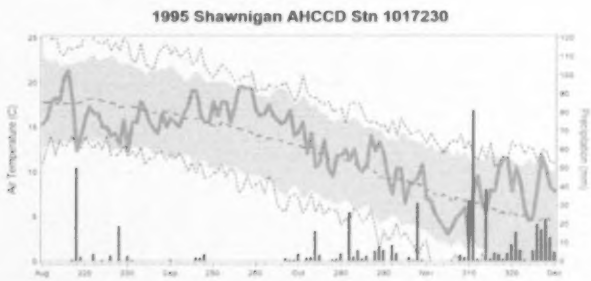

1994 LowerCowichan Stn 08HA011 Discharge
Flow (cms)

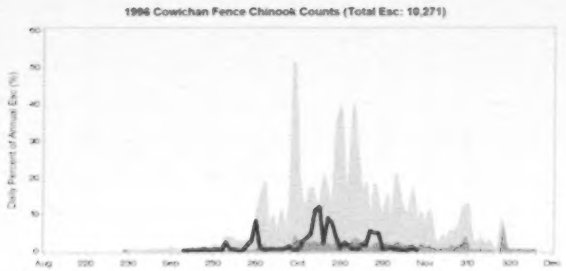

1995 LowerCowichan Stn 08HA011 Discharge
Flow (cms)

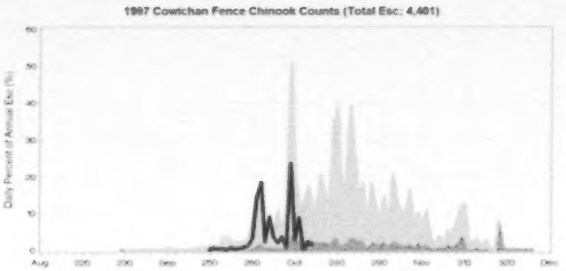

1994 Cowichan Water Temperature
Temperature (C)


1995 Cowichan Water Temperature
Temperature (C)

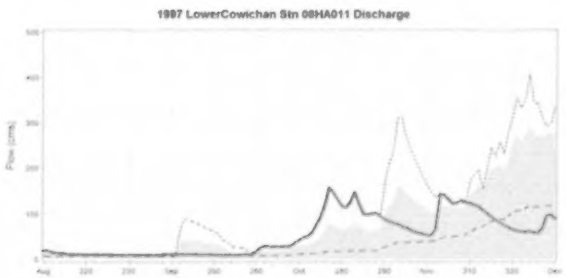
1994 Shawnigan AHCCD Stn 1017230
Air Temperature (C)

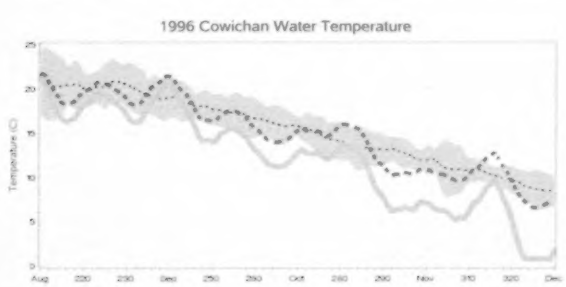

1995 Shawnigan AHCCD Stn 1017230
Air Temperature (C)

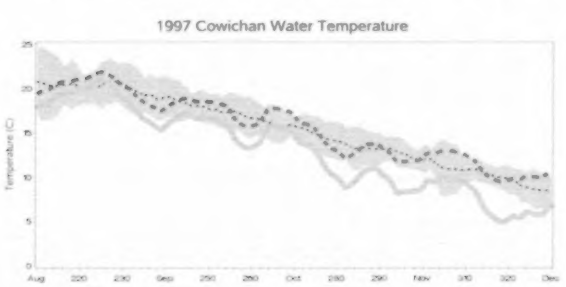

1996 Cowichan Fence Chinook Counts (Total Esc: 10,271)
Daily Percent of Annual Esc (%)

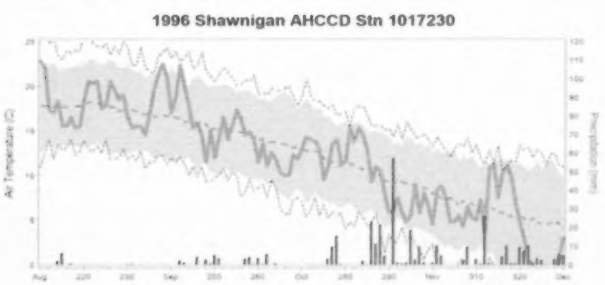

1997 Cowichan Fence Chinook Counts (Total Esc: 4,401)
Daily Percent of Annual Esc (%)

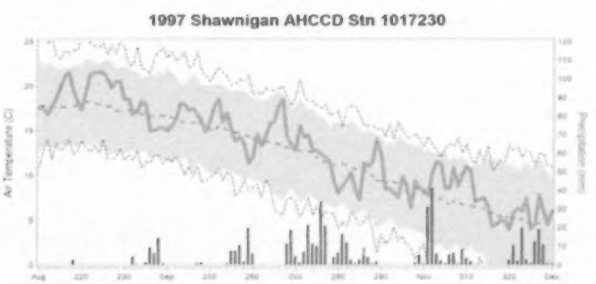
1996 LowerCowichan Stn 08HA011 Discharge
Flow (cms)

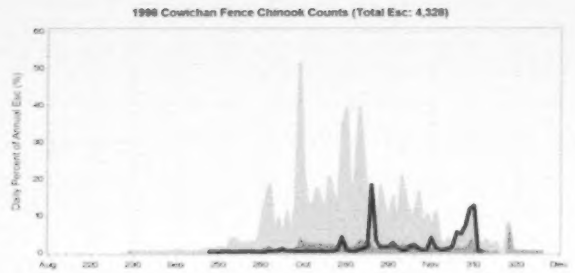

1997 LowerCowichan Stn 08HA011 Discharge
Flow (cms)

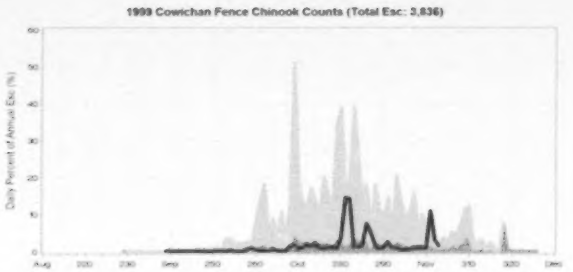

1996 Cowichan Water Temperature
Temperature (C)


1997 Cowichan Water Temperature
Temperature (C)

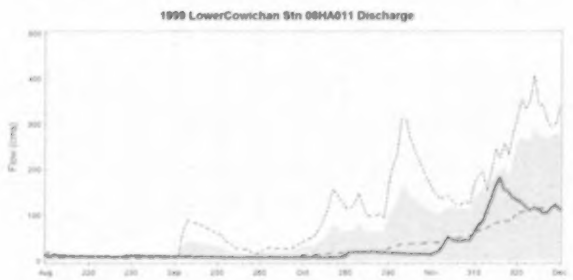

1996 Shawnigan AHCCD Stn 1017230
Air Temperature (C)
Precipitation (mm)

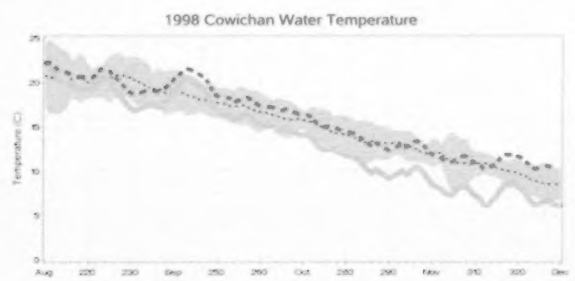

1997 Shawnigan AHCCD Stn 1017230
Air Temperature (C)
Precipitation (mm)

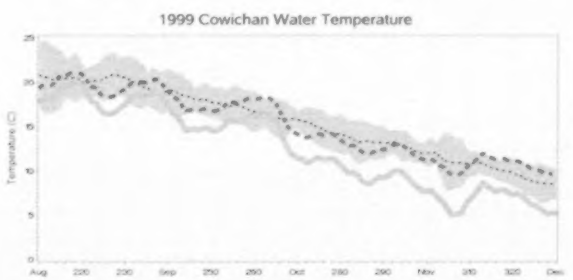

1998 Cowichan Fence Chinook Counts (Total Esc: 4,328)
Daily Percent of Annual Esc (%)

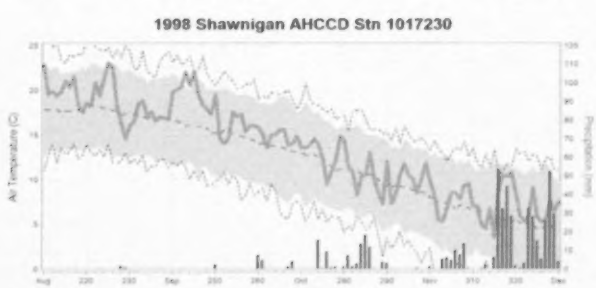

1999 Cowichan Fence Chinook Counts (Total Esc: 3,836)
Daily Percent of Annual Esc (%)

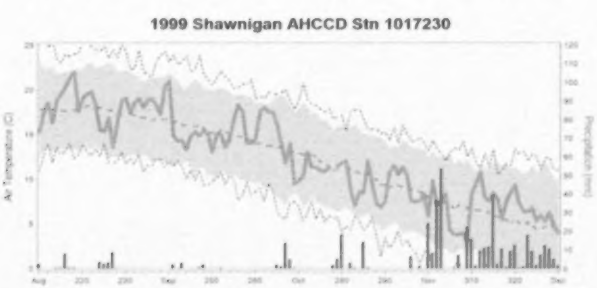
1998 LowerCowichan Stn 08HA011 Discharge
Flow (cms)

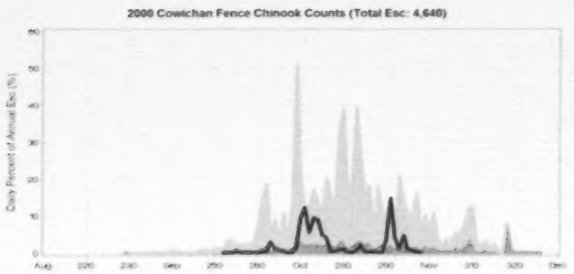

1999 LowerCowichan Stn 08HA011 Discharge
Flow (cms)

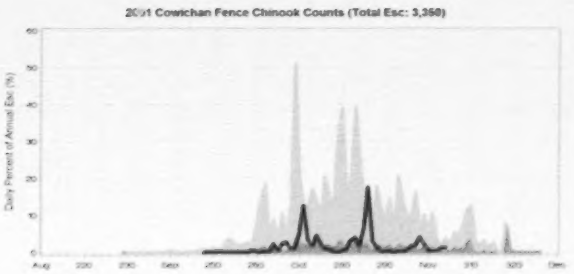

1998 Cowichan Water Temperature
Temperature (C)

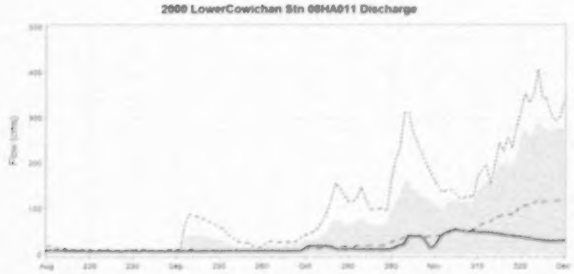

1999 Cowichan Water Temperature
Temperature (C)

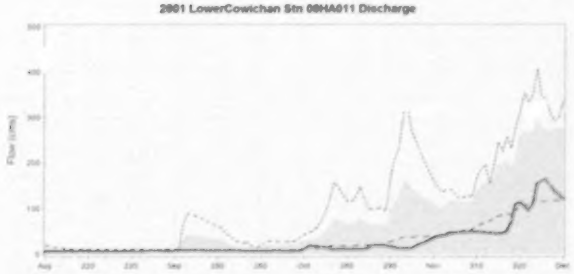

1998 Shawnigan AHCCD Stn 1017230
Air Temperature (C)
Precipitation (mm)

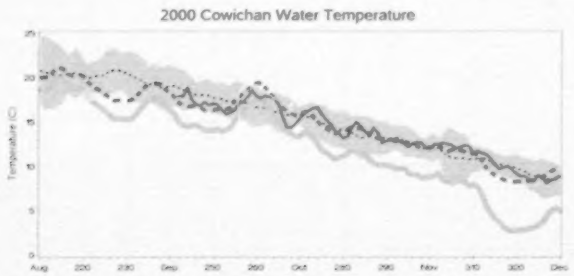

1999 Shawnigan AHCCD Stn 1017230
Air Temperature (C)
Precipitation (mm)

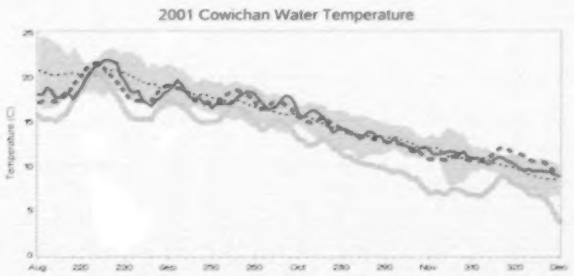

2000 Cowichan Fence Chinook Counts (Total Esc: 4,640)
Daily Percent of Annual Esc (%)

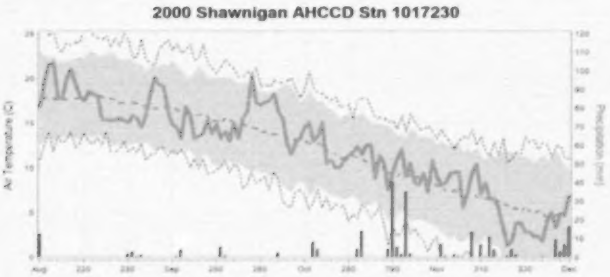

2001 Cowichan Fence Chinook Counts (Total Esc: 3,350)
Daily Percent of Annual Esc (%)

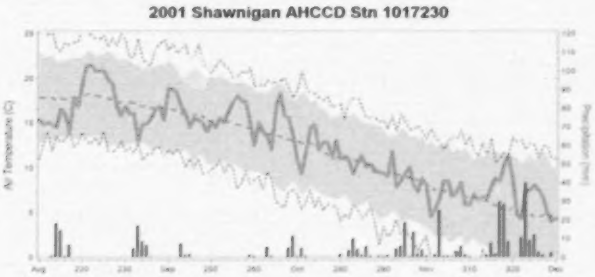

2000 LowerCowichan Stn 08HA011 Discharge
Flow (cms)

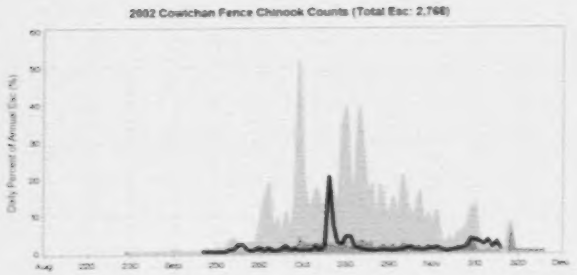

2001 LowerCowichan Stn 08HA011 Discharge
Flow (cms)

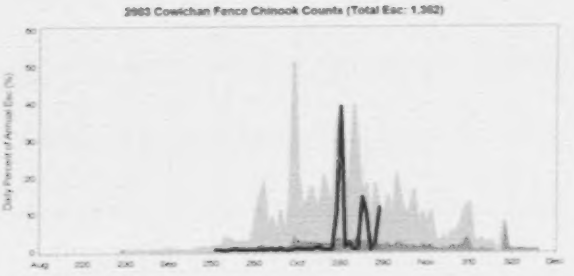

2000 Cowichan Water Temperature
Temperature (C)

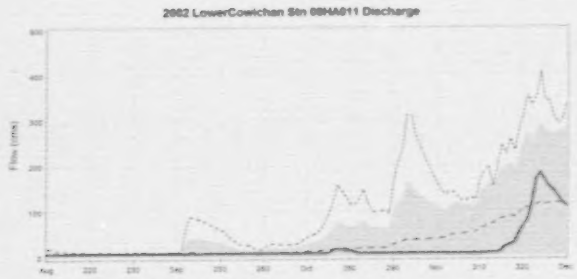

2001 Cowichan Water Temperature
Temperature (C)

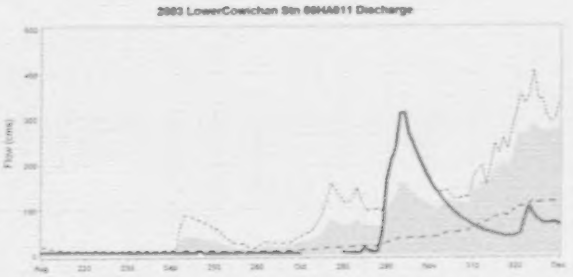

2000 Shawnigan AHCCD Stn 1017230
Air Temperature (C)
Precipitation (mm)

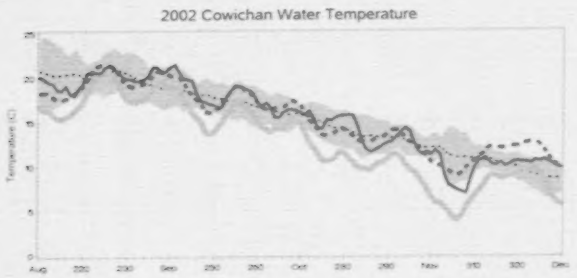

2001 Shawnigan AHCCD Stn 1017230
Air Temperature (C)
Precipitation (mm)

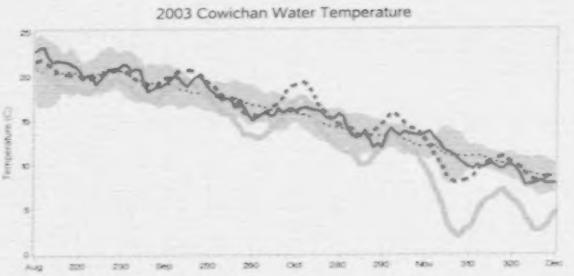

2002 Cowichan Fence Chinook Counts (Total Esc: 2,766)
Daily Percent of Annual Esc (%)

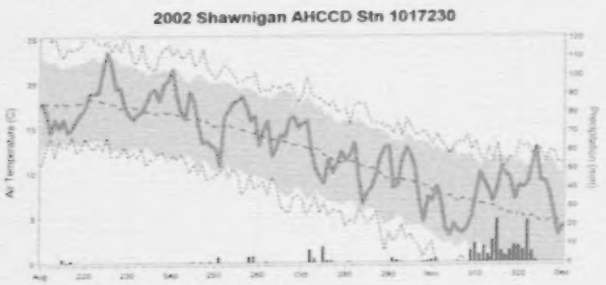

2003 Cowichan Fence Chinook Counts (Total Esc: 1,382)
Daily Percent of Annual Esc (%)

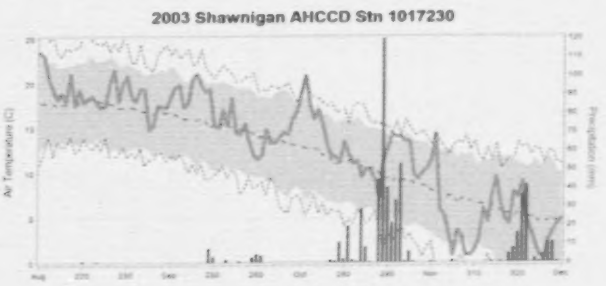

2002 LowerCowichan Stn 08HA011 Discharge
Flow (cms)

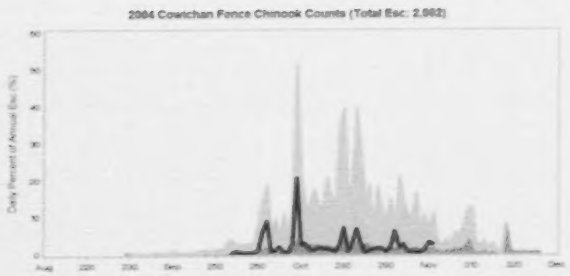

2003 LowerCowichan Stn 08HA011 Discharge
Flow (cms)

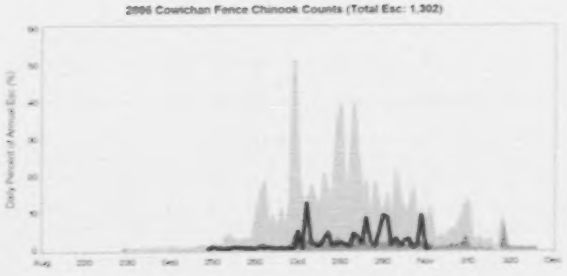

2002 Cowichan Water Temperature
Temperature (C)

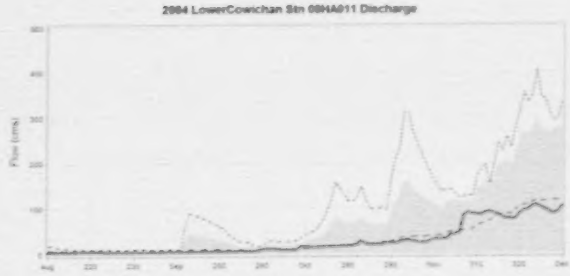

2003 Cowichan Water Temperature
Temperature (C)

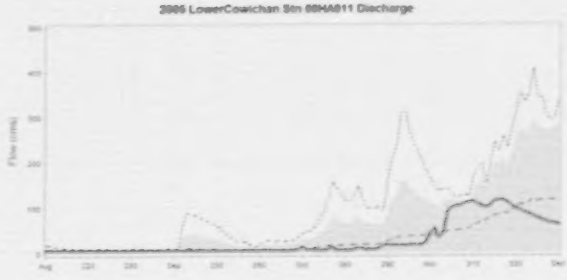

2002 Shawnigan AHCCD Stn 1017230
Air Temperature (C)
Precipitation (mm)

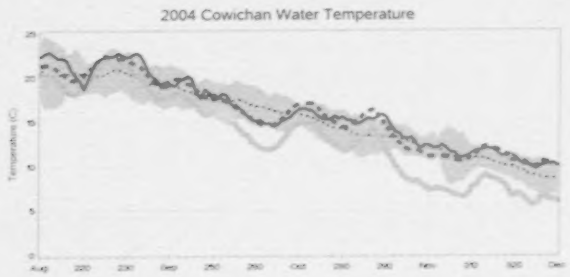

2003 Shawnigan AHCCD Stn 1017230
Air Temperature (C)
Precipitation (mm)

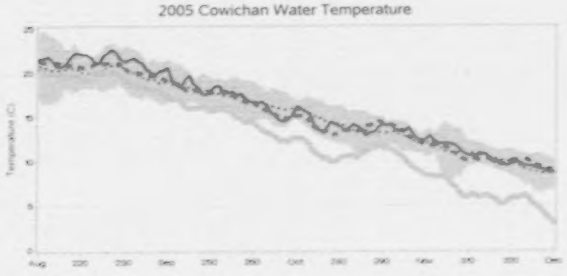

2004 Cowichan Fence Chinook Counts (Total Esc: 2,982)

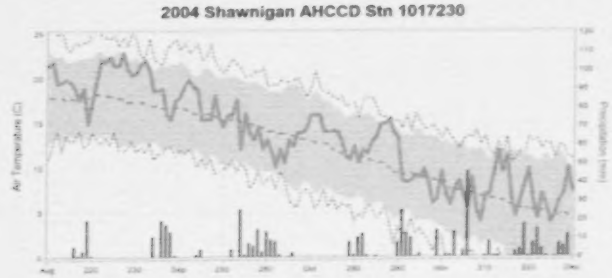

2006 Cowichan Fence Chinook Counts (Total Esc: 1,302)

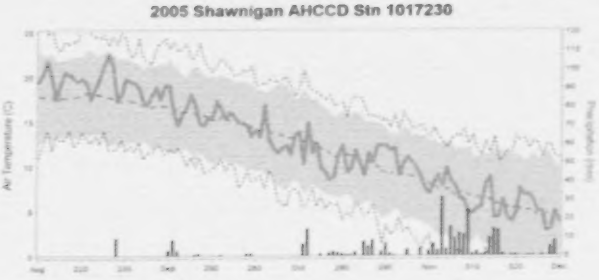

2004 LowerCowichan Stn 08HA011 Discharge

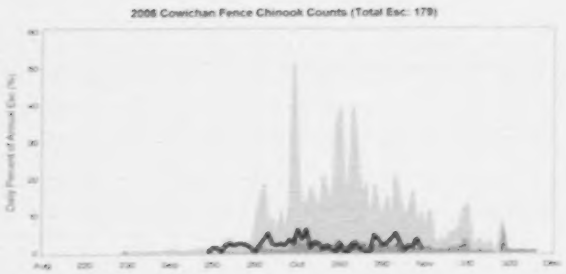

2005 LowerCowichan Stn 08HA011 Discharge

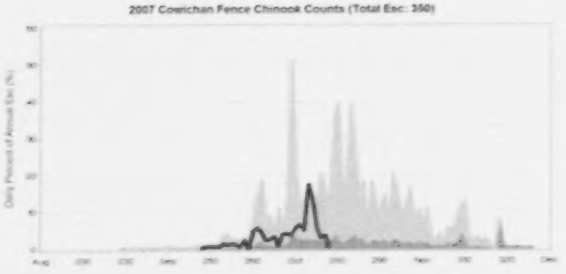

2004 Cowichan Water Temperature


2005 Cowichan Water Temperature

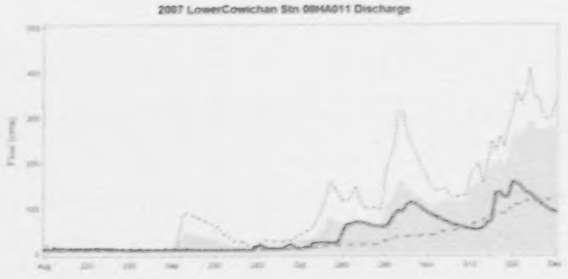

2004 Shawnigan AHCCD Stn 1017230

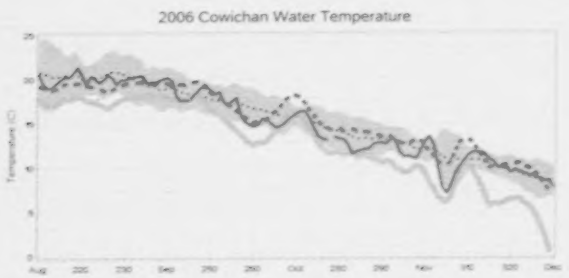

2005 Shawnigan AHCCD Stn 1017230

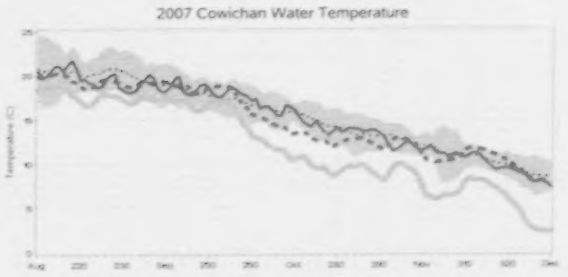

2006 Cowichan Fence Chinook Counts (Total Esc: 179)

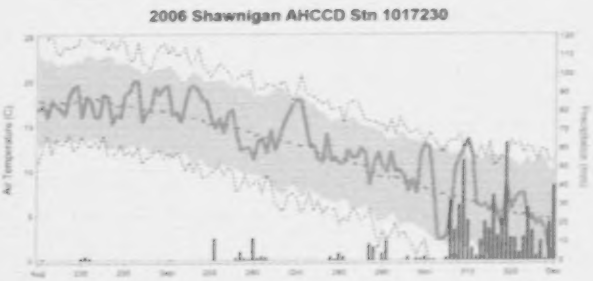

2007 Cowichan Fence Chinook Counts (Total Esc: 350)

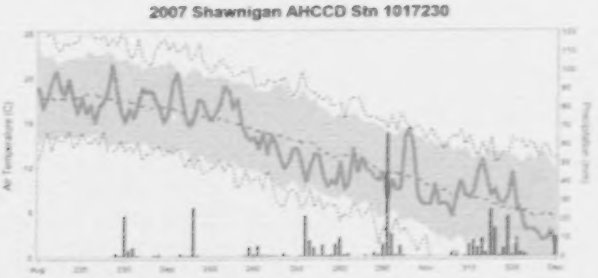
2006 LowerCowichan Stn 08HA011 Discharge

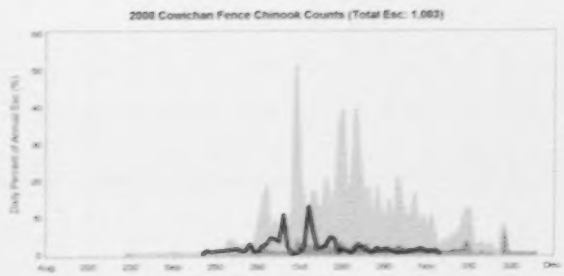

2007 LowerCowichan Stn 08HA011 Discharge

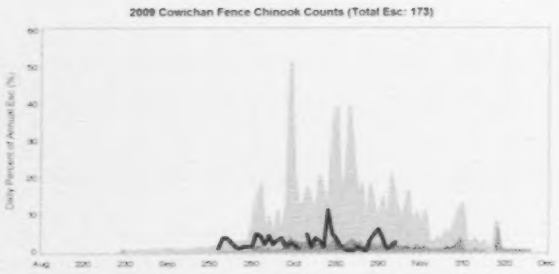

2006 Cowichan Water Temperature

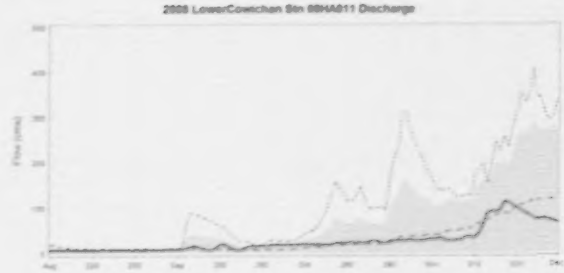

2007 Cowichan Water Temperature

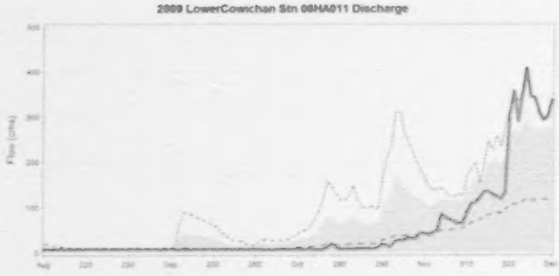

2006 Shawnigan AHCCD Stn 1017230

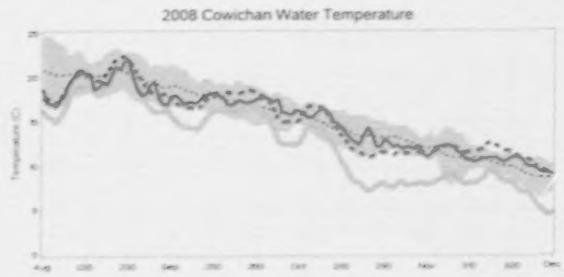

2007 Shawnigan AHCCD Stn 1017230

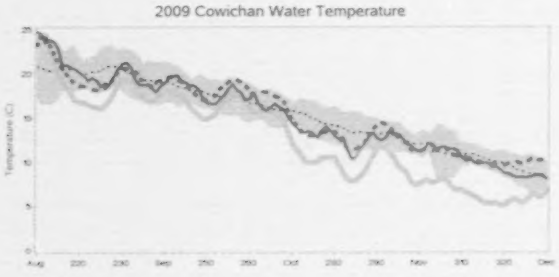

2008 Cowichan Fence Chinook Counts (Total Esc: 1,083)

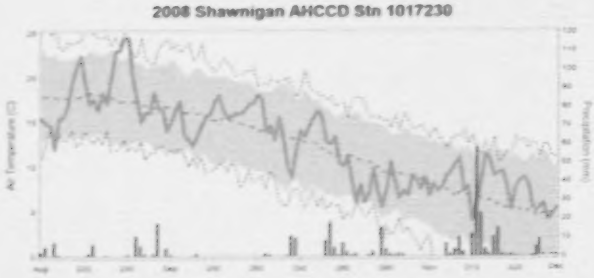

2009 Cowichan Fence Chinook Counts (Total Esc: 173)

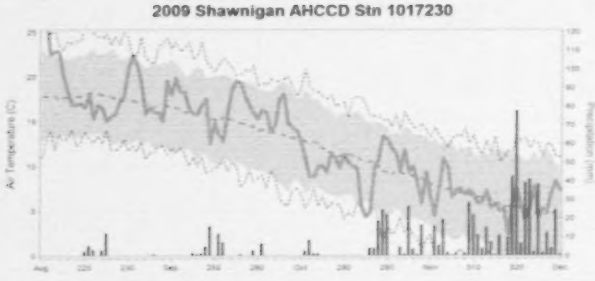

2008 LowerCowichan Stn 08HA011 Discharge

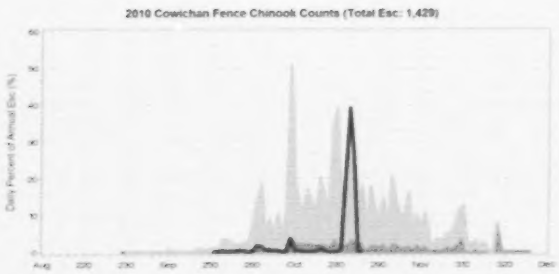

2009 LowerCowichan Stn 08HA011 Discharge

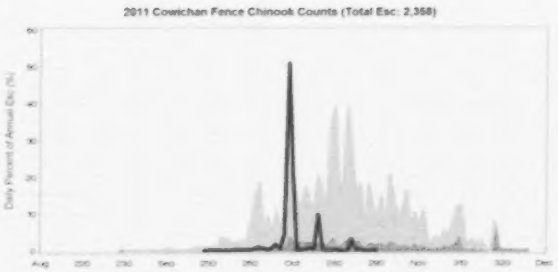

2008 Cowichan Water Temperature

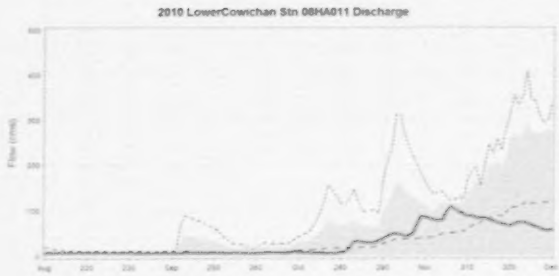

2009 Cowichan Water Temperature

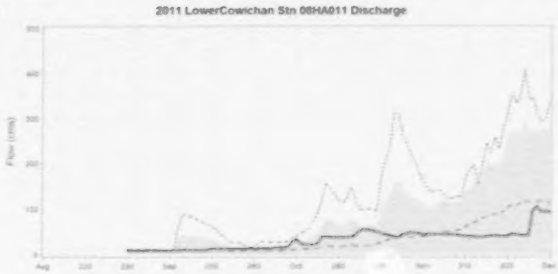

2008 Shawnigan AHCCD Stn 1017230

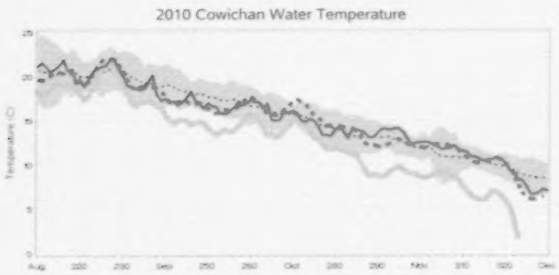

2009 Shawnigan AHCCD Stn 1017230

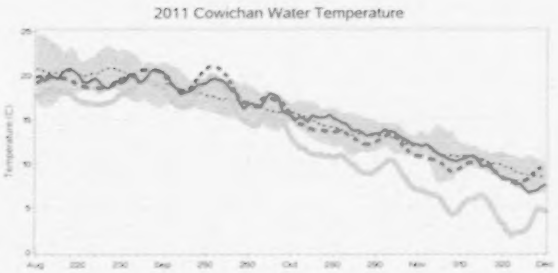

2010 Cowichan Fence Chinook Counts (Total Esc.: 1,429)

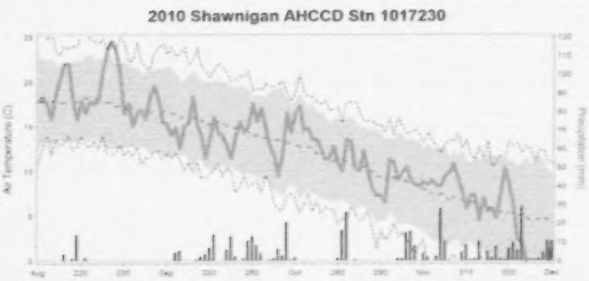

2011 Cowichan Fence Chinook Counts (Total Esc.: 2,358)

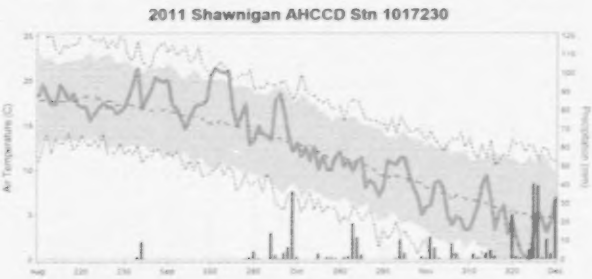

2010 LowerCowichan Stn 08HA011 Discharge

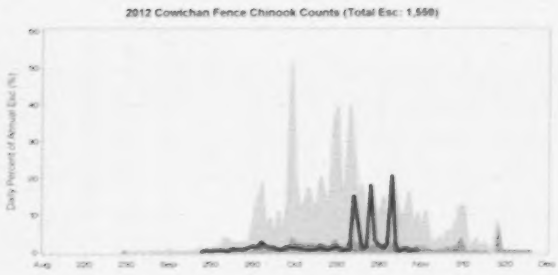

2011 LowerCowichan Stn 08HA011 Discharge

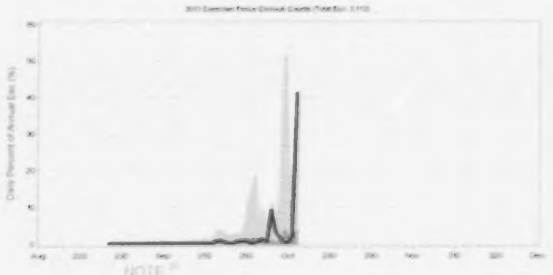

2010 Cowichan Water Temperature

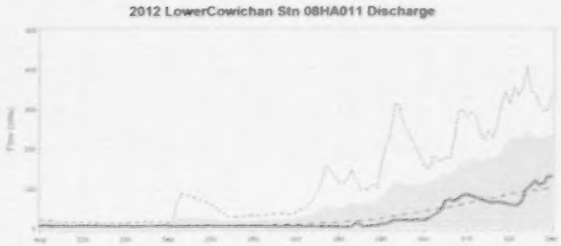

2011 Cowichan Water Temperature

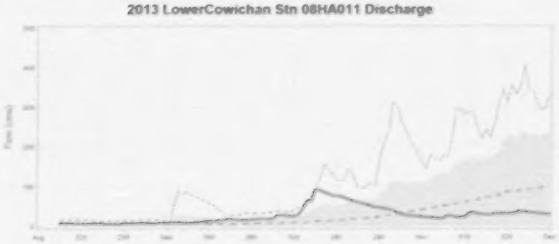

2010 Shawnigan AHCCD Stn 1017230

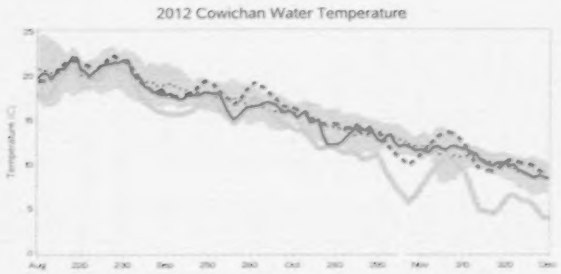

2011 Shawnigan AHCCD Stn 1017230

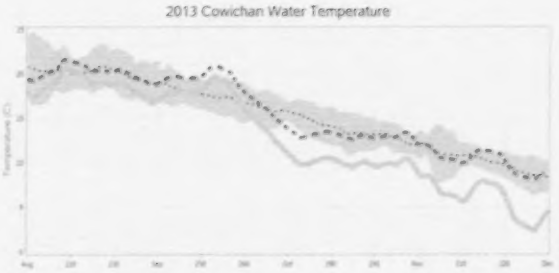


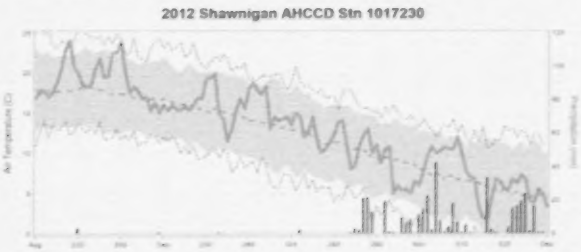


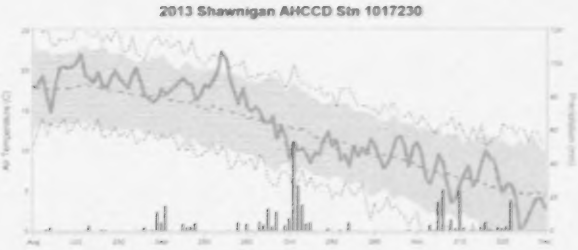




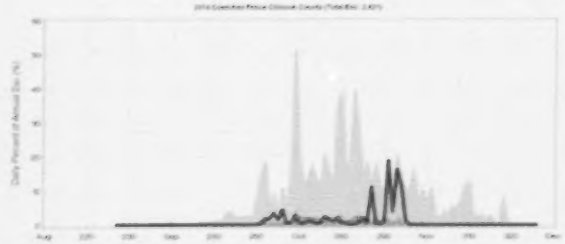




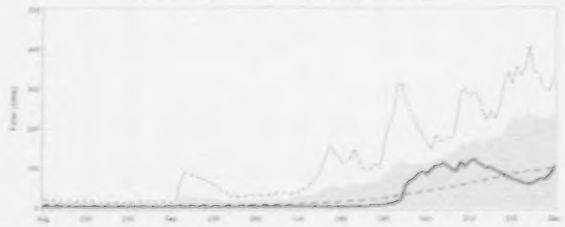




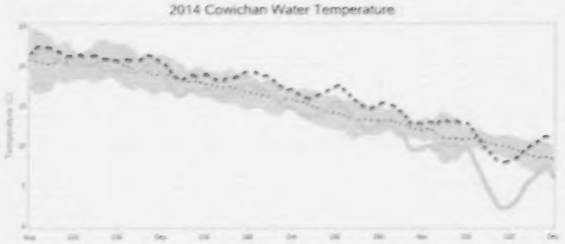
[36] Note: Chinook counts after September 29th were not reliable due to high flows and turbidity.



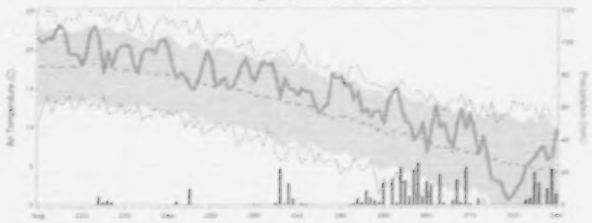
2014 LowerCowichan Stn 08HA011 Discharge



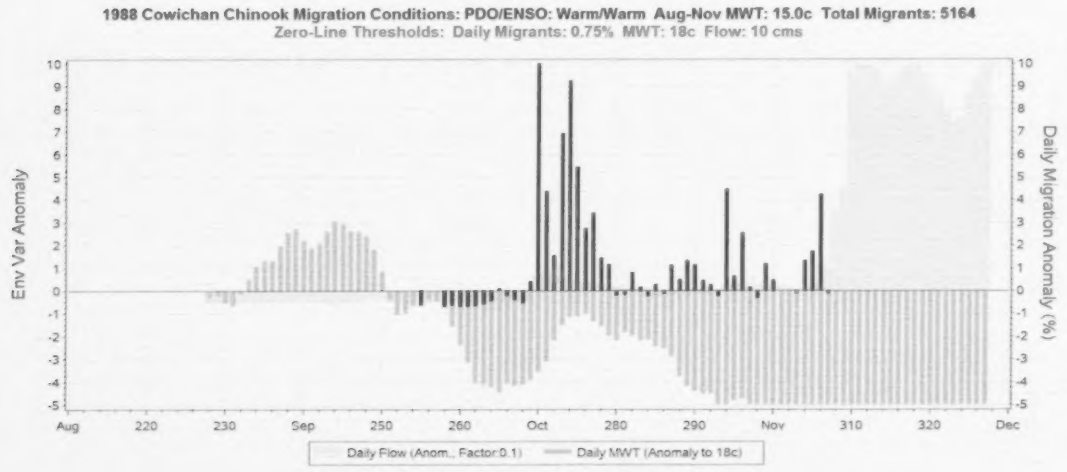
2014 Cowichan Water Temperature

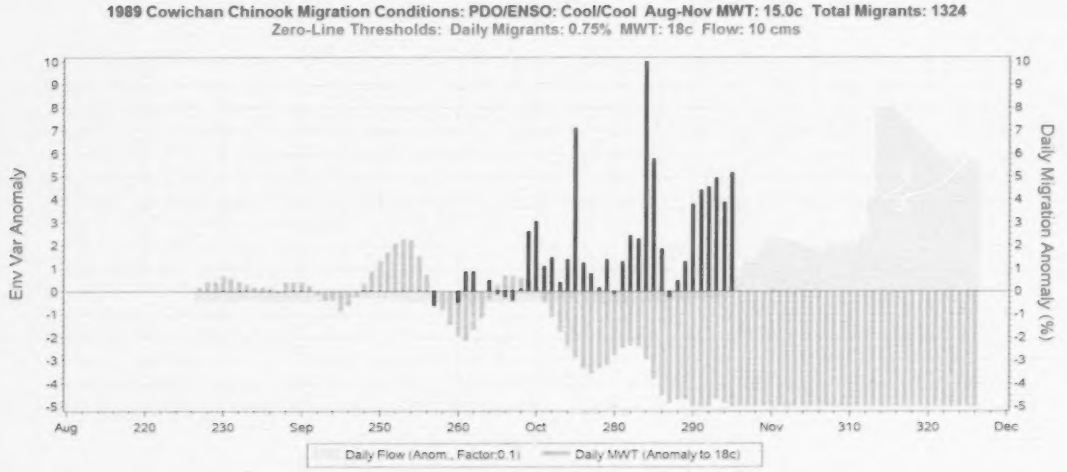


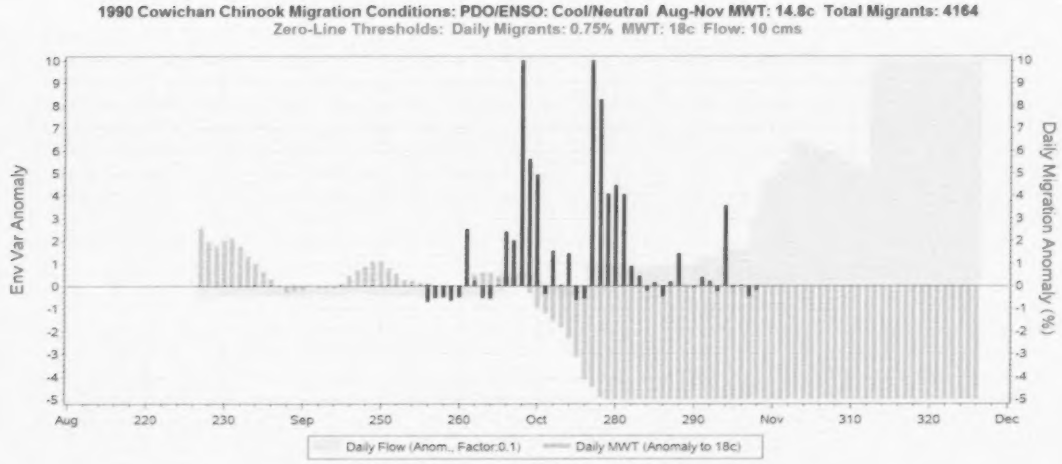
2014 Shawnigan AHCCD Stn 1017230

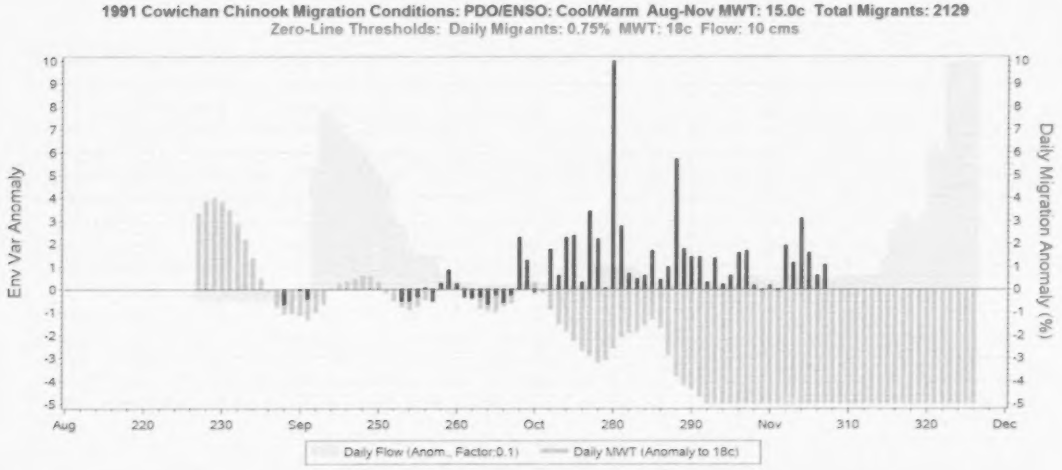


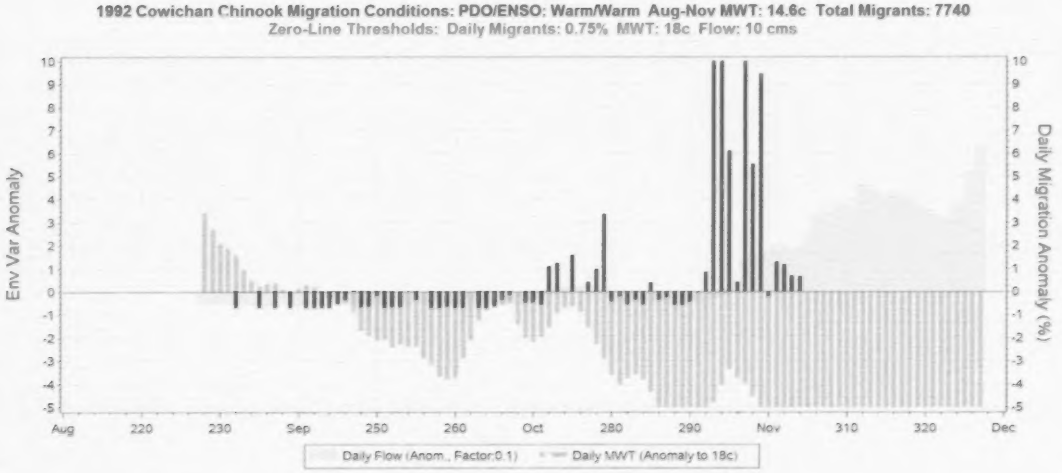
Appendix B. Annual anomaly plots for Cowichan Chinook migration, water temperature (estimated), and river discharge (flow factored by 0.10 to fit on y-axis). Zero-line thresholds:
(a) Daily migration rate = 0.75% (50th percentile of non-zero daily migration rates (1988-2012, 2014);
(b) Lower Cowichan water temperature = 18°C;
(c) Lower Cowichan discharge = 10 cms.
See also Table 4 for documentation of annual pulsed flow timing.

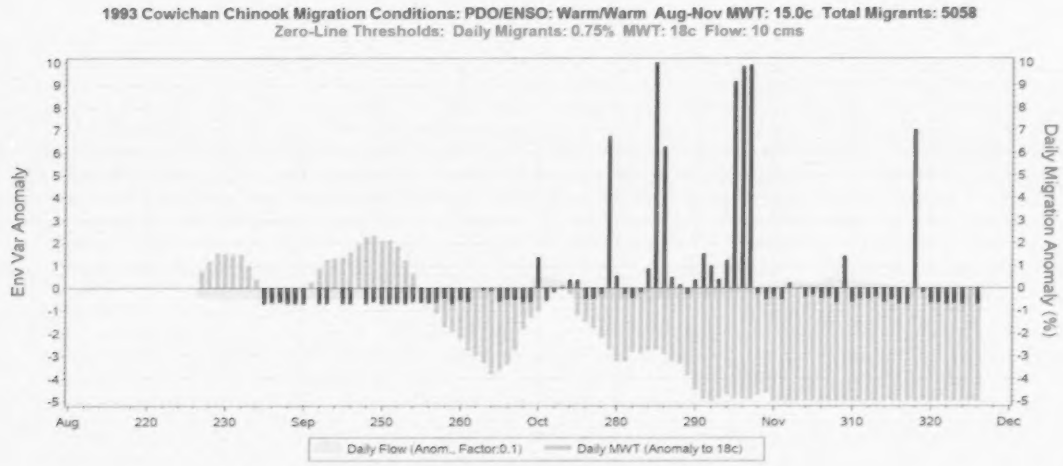

1988 Cowichan Chinook Migration Conditions: PDO/ENSO: Warm/Warm Aug-Nov MWT: 15.0c Total Migrants: 5164
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms
Env Var Anomaly
Daily Migration Anomaly (%)
Aug
Sep
Oct
Nov
Dec
Daily Flow (Anom., Factor:0.1)
Daily MWT (Anomaly to 18c)

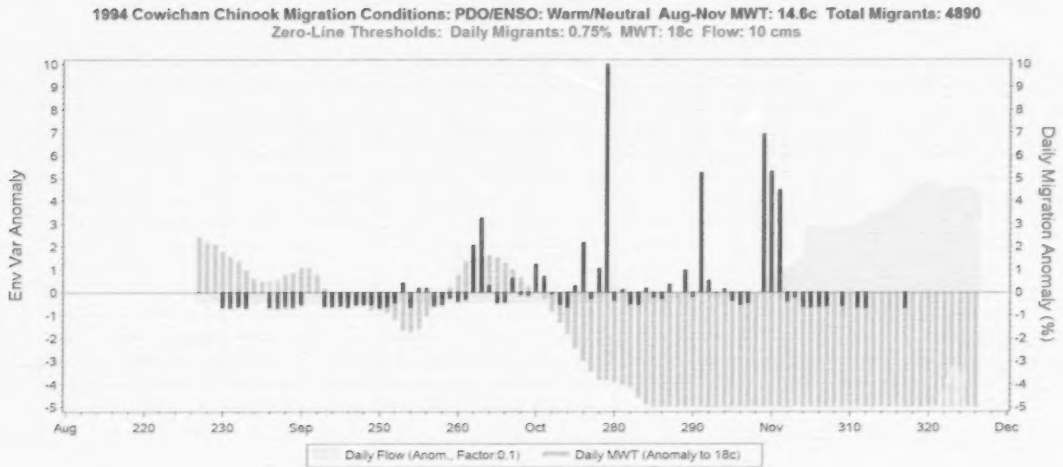

1989 Cowichan Chinook Migration Conditions: PDO/ENSO: Cool/Cool Aug-Nov MWT: 15.0c Total Migrants: 1324
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms
Env Var Anomaly
Daily Migration Anomaly (%)
Aug
Sep
Oct
Nov
Dec
Daily Flow (Anom., Factor:0.1)
Daily MWT (Anomaly to 18c)

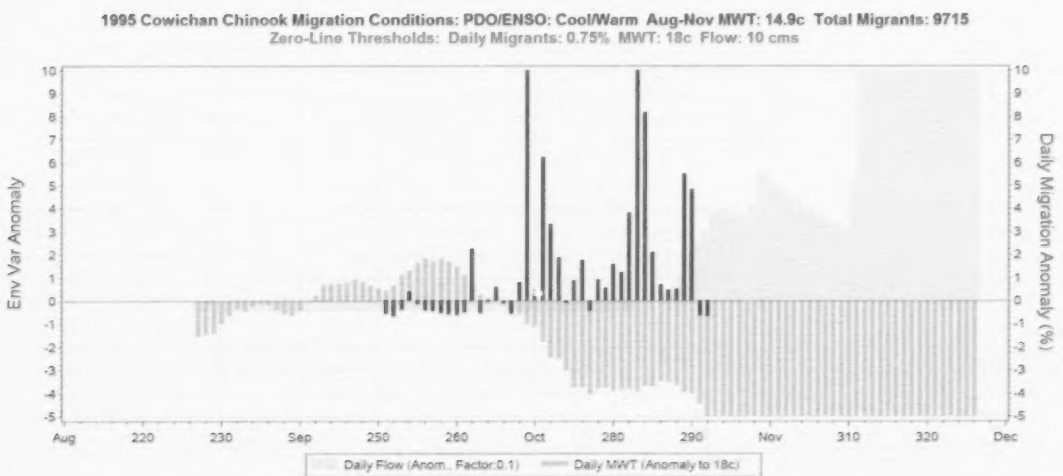

1990 Cowichan Chinook Migration Conditions: PDO/ENSO: Cool/Neutral Aug-Nov MWT: 14.8c Total Migrants: 4164
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms
Env Var Anomaly
Daily Migration Anomaly (%)
Aug
Sep
Oct
Nov
Dec
Daily Flow (Anom., Factor:0.1)
Daily MWT (Anomaly to 18c)


1991 Cowichan Chinook Migration Conditions: PDO/ENSO: Cool/Warm Aug-Nov MWT: 15.0c Total Migrants: 2129
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms
Env Var Anomaly
Daily Migration Anomaly (%)
Aug
Sep
Oct
Nov
Dec
Daily Flow (Anom., Factor:0.1)
Daily MWT (Anomaly to 18c)

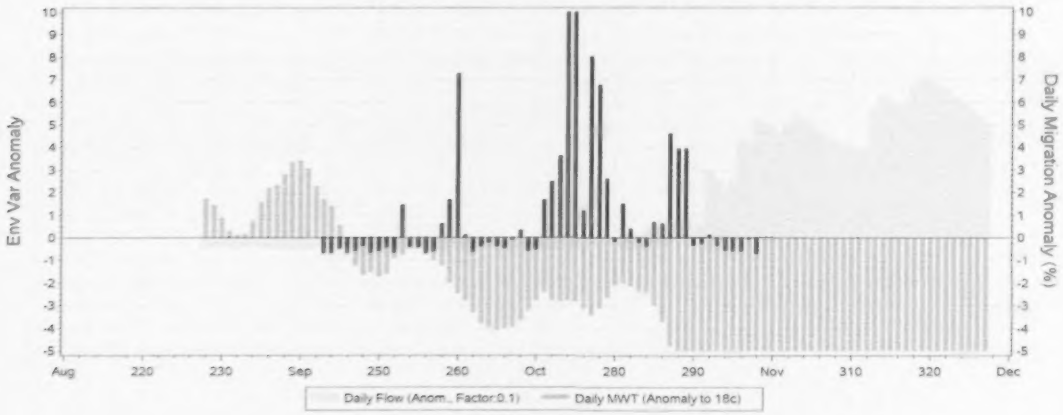

1992 Cowichan Chinook Migration Conditions: PDO/ENSO: Warm/Warm Aug-Nov MWT: 14.6c Total Migrants: 7740
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms
Env Var Anomaly
Daily Migration Anomaly (%)
Aug
Sep
Oct
Nov
Dec
Daily Flow (Anom., Factor:0.1)
Daily MWT (Anomaly to 18c)


1993 Cowichan Chinook Migration Conditions: PDO/ENSO: Warm/Warm Aug-Nov MWT: 15.0c Total Migrants: 5058
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms
Env Var Anomaly
Daily Migration Anomaly (%)
Aug 220 230 Sep 250 260 Oct 280 290 Nov 310 320 Dec
Daily Flow (Anom., Factor:0.1)
Daily MWT (Anomaly to 18c)

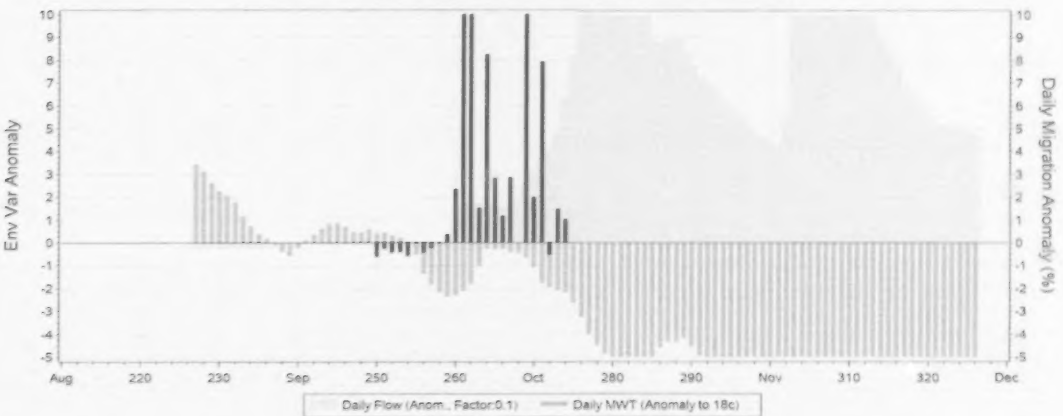

1994 Cowichan Chinook Migration Conditions: PDO/ENSO: Warm/Neutral Aug-Nov MWT: 14.6c Total Migrants: 4890
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms
Env Var Anomaly
Daily Migration Anomaly (%)
Aug 220 230 Sep 250 260 Oct 280 290 Nov 310 320 Dec
Daily Flow (Anom., Factor:0.1)
Daily MWT (Anomaly to 18c)


1995 Cowichan Chinook Migration Conditions: PDO/ENSO: Cool/Warm Aug-Nov MWT: 14.9c Total Migrants: 9715
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms
Env Var Anomaly
Daily Migration Anomaly (%)
Aug 220 230 Sep 250 260 Oct 280 290 Nov 310 320 Dec
Daily Flow (Anom., Factor:0.1)
Daily MWT (Anomaly to 18c)

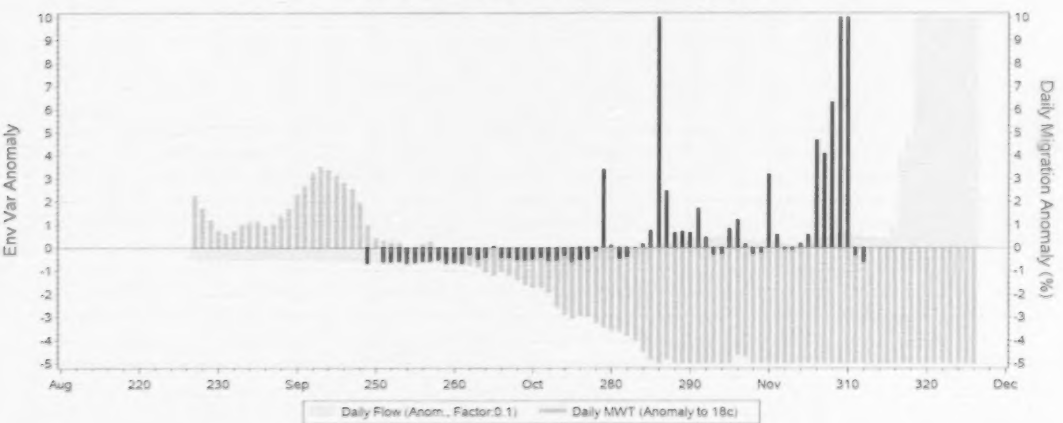
1996 Cowichan Chinook Migration Conditions: PDO/ENSO: Warm/Neutral Aug-Nov MWT: 14.1c Total Migrants: 10271
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms

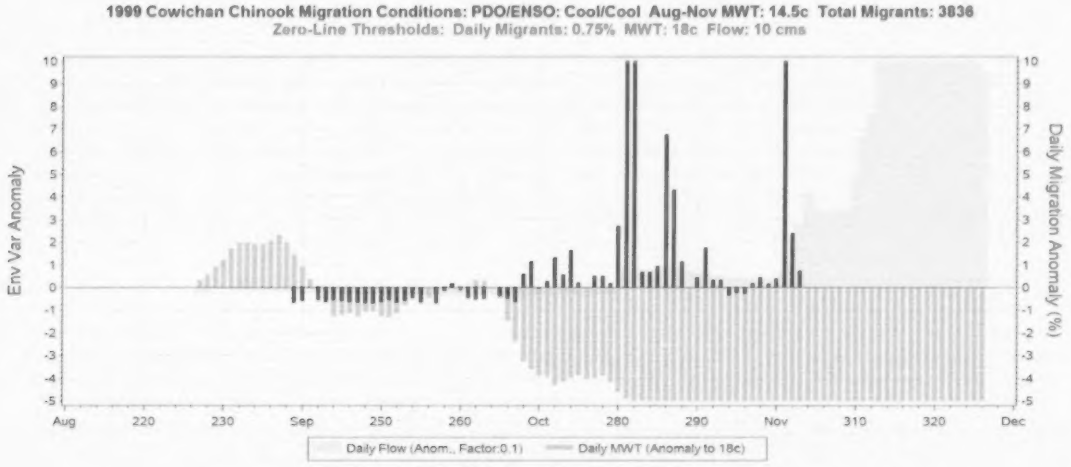


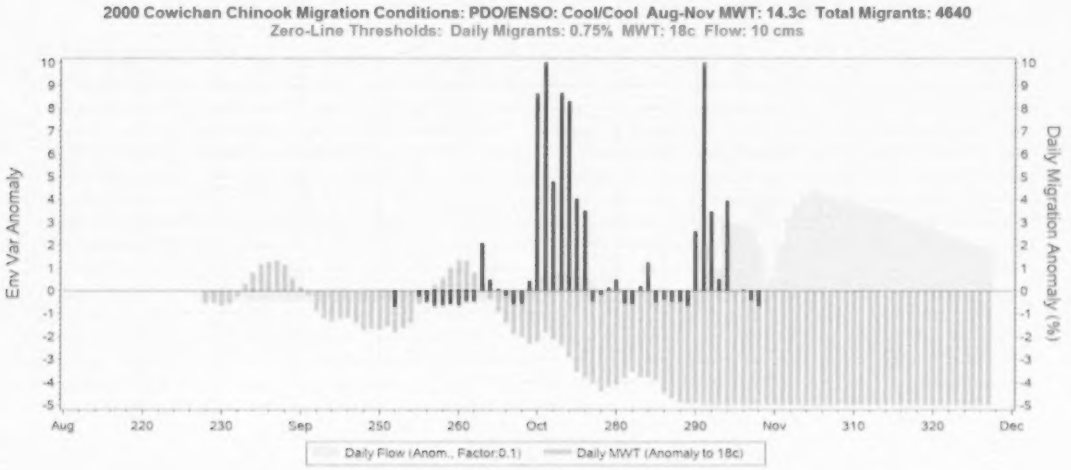
1997 Cowichan Chinook Migration Conditions: PDO/ENSO: Warm/Neutral Aug-Nov MWT: 14.9c Total Migrants: 4401
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms

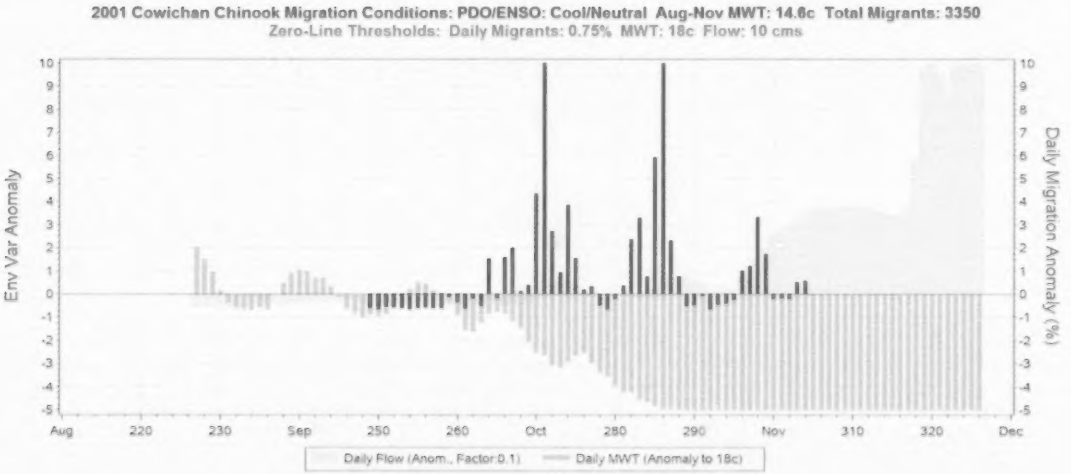


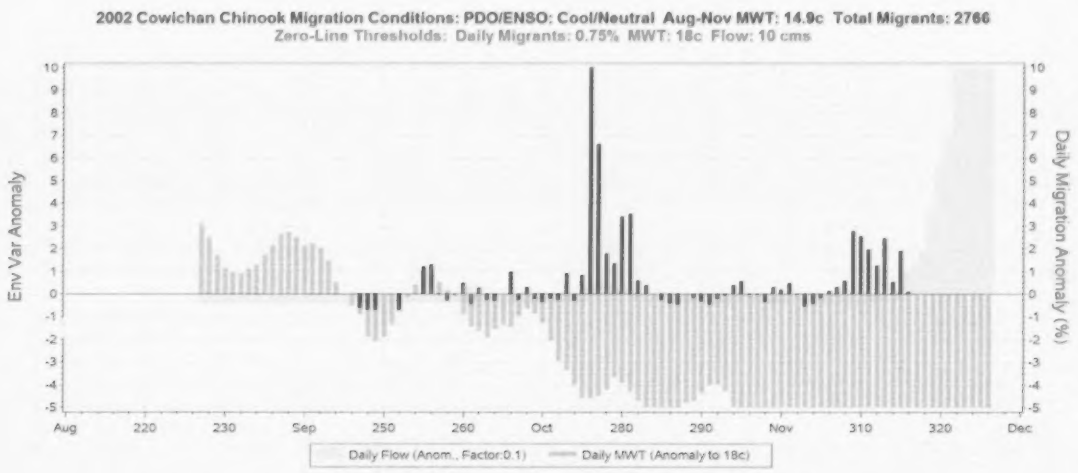
1998 Cowichan Chinook Migration Conditions: PDO/ENSO: Warm/Warm Aug-Nov MWT: 15.2c Total Migrants: 4328
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms



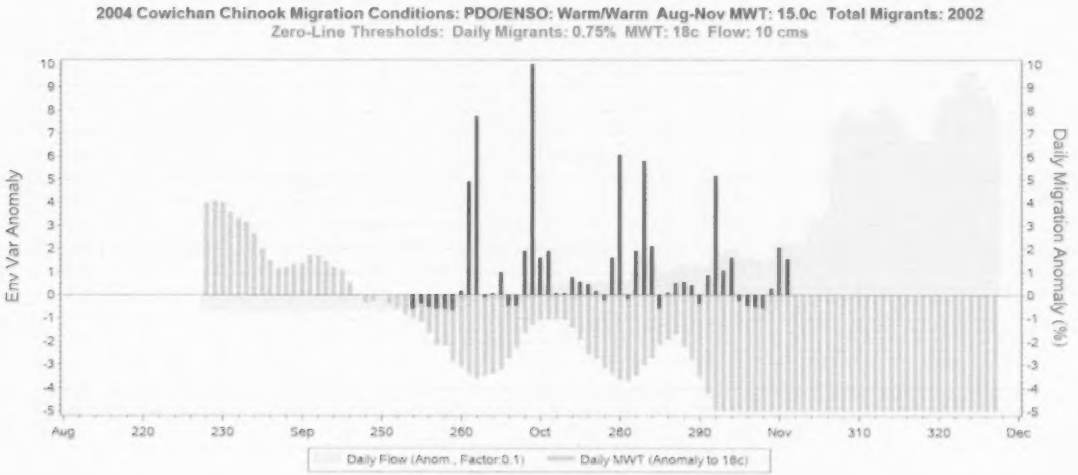

1999 Cowichan Chinook Migration Conditions: PDO/ENSO: Cool/Cool Aug-Nov MWT: 14.5c Total Migrants: 3836
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms
Env Var Anomaly
Daily Migration Anomaly (%)
Aug
Sep
Oct
Nov
Dec
Daily Flow (Anom., Factor:0.1)
Daily MWT (Anomaly to 18c)

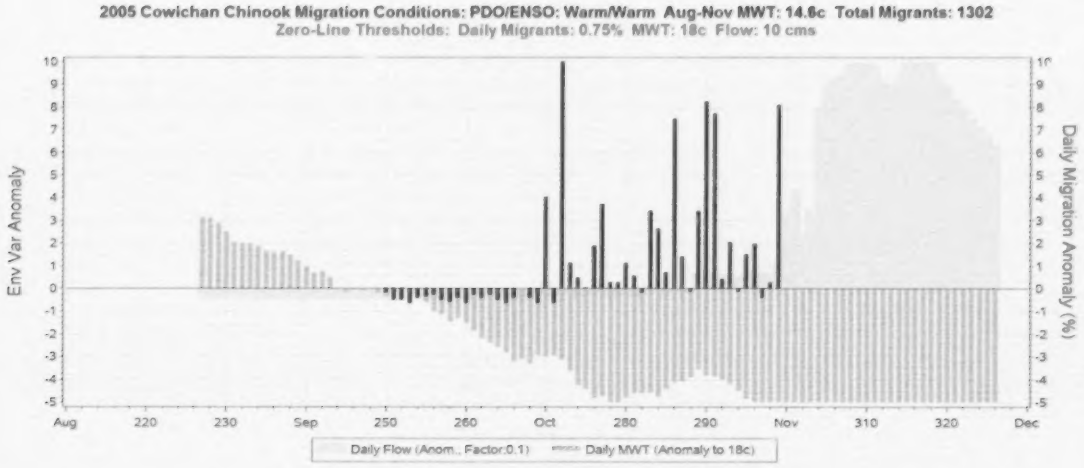

2000 Cowichan Chinook Migration Conditions: PDO/ENSO: Cool/Cool Aug-Nov MWT: 14.3c Total Migrants: 4640
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms
Env Var Anomaly
Daily Migration Anomaly (%)
Aug
Sep
Oct
Nov
Dec
Daily Flow (Anom., Factor:0.1)
Daily MWT (Anomaly to 18c)

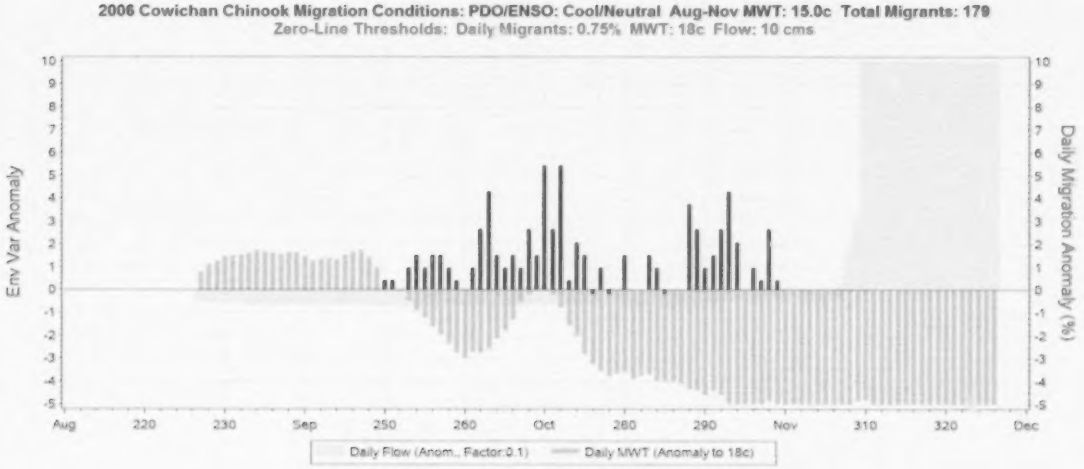

2001 Cowichan Chinook Migration Conditions: PDO/ENSO: Cool/Neutral Aug-Nov MWT: 14.6c Total Migrants: 3350
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms
Env Var Anomaly
Daily Migration Anomaly (%)
Aug
Sep
Oct
Nov
Dec
Daily Flow (Anom., Factor:0.1)
Daily MWT (Anomaly to 18c)

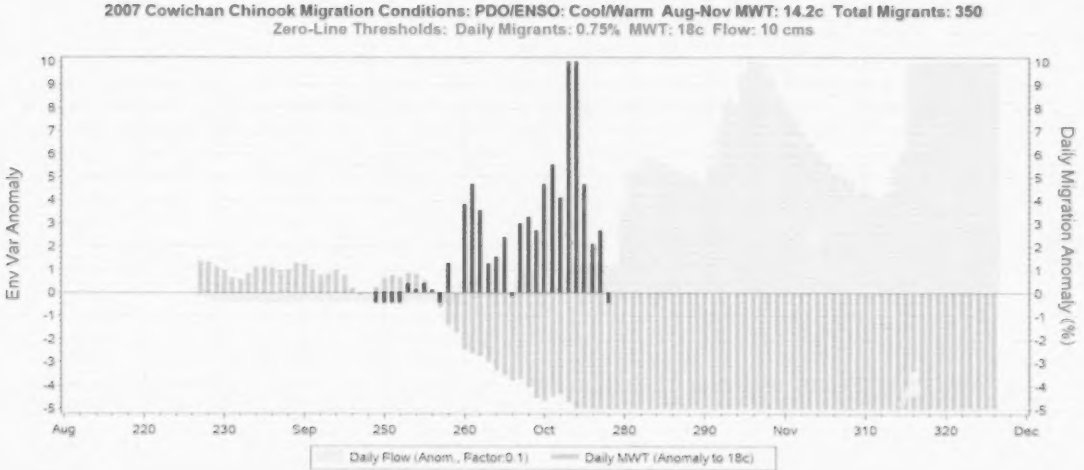

2002 Cowichan Chinook Migration Conditions: PDO/ENSO: Cool/Neutral Aug-Nov MWT: 14.9c Total Migrants: 2766
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms
Env Var Anomaly
Daily Migration Anomaly (%)
Aug
Sep
Oct
Nov
Dec
Daily Flow (Anom., Factor:0.1)
Daily MWT (Anomaly to 18c)

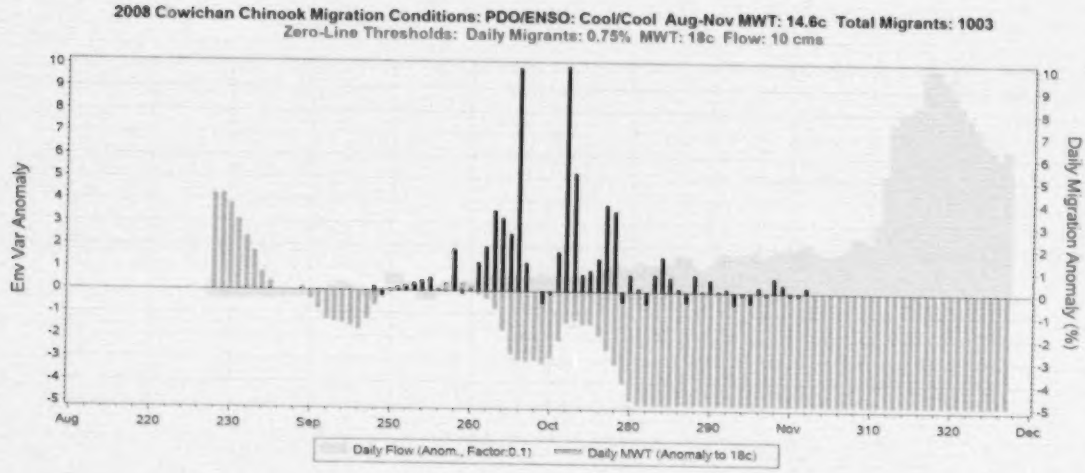
2003 Cowichan Chinook Migration Conditions: PDO/ENSO: Warm/Warm Aug-Nov MWT: 15.1c Total Migrants: 1352
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms
Env Var Anomaly
Daily Migration Anomaly (%)
Aug
Sep
Oct
Nov
Dec
Daily Flow (Anom., Factor:0.1)
Daily MWT (Anomaly to 18c)

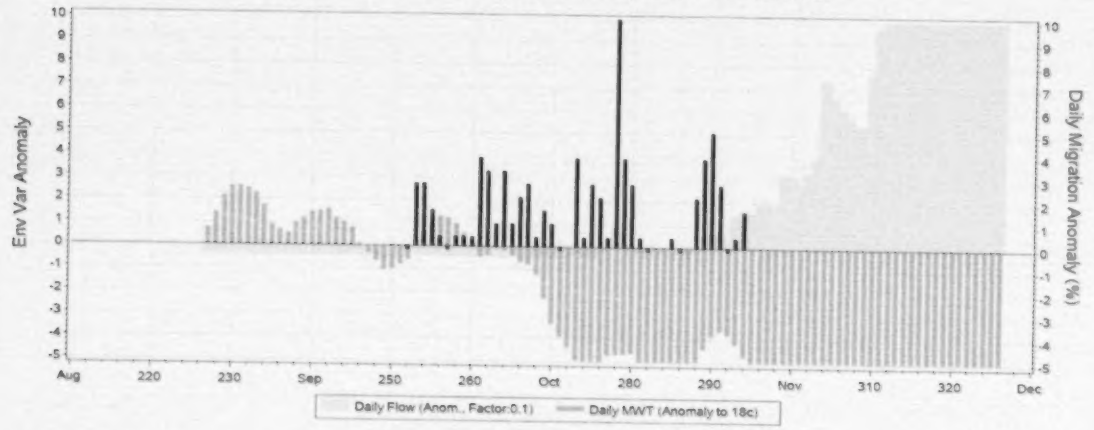

2004 Cowichan Chinook Migration Conditions: PDO/ENSO: Warm/Warm Aug-Nov MWT: 15.0c Total Migrants: 2002
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms
Env Var Anomaly
Daily Migration Anomaly (%)
Aug
Sep
Oct
Nov
Dec
Daily Flow (Anom., Factor:0.1)
Daily MWT (Anomaly to 18c)

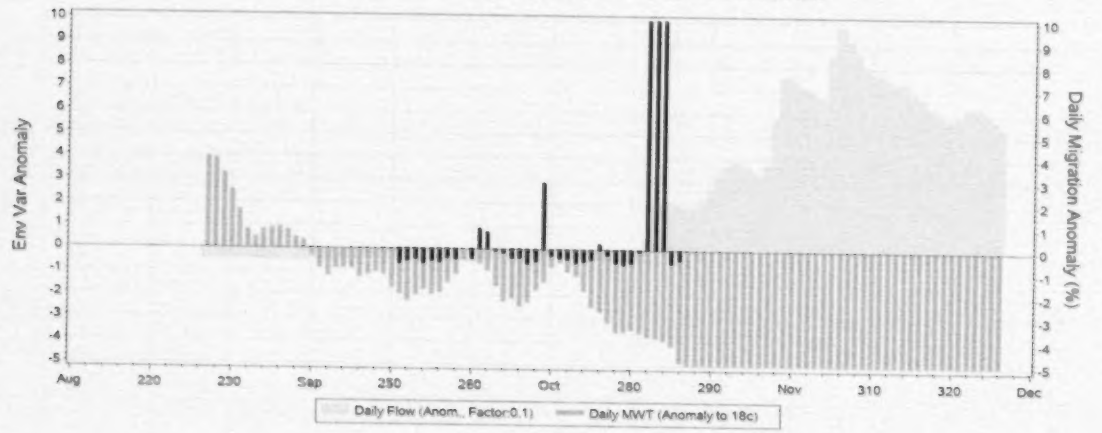

2005 Cowichan Chinook Migration Conditions: PDO/ENSO: Warm/Warm Aug-Nov MWT: 14.6c Total Migrants: 1302
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms
Env Var Anomaly
Daily Migration Anomaly (%)
Aug
Sep
Oct
Nov
Dec
Daily Flow (Anom., Factor:0.1)
Daily MWT (Anomaly to 18c)

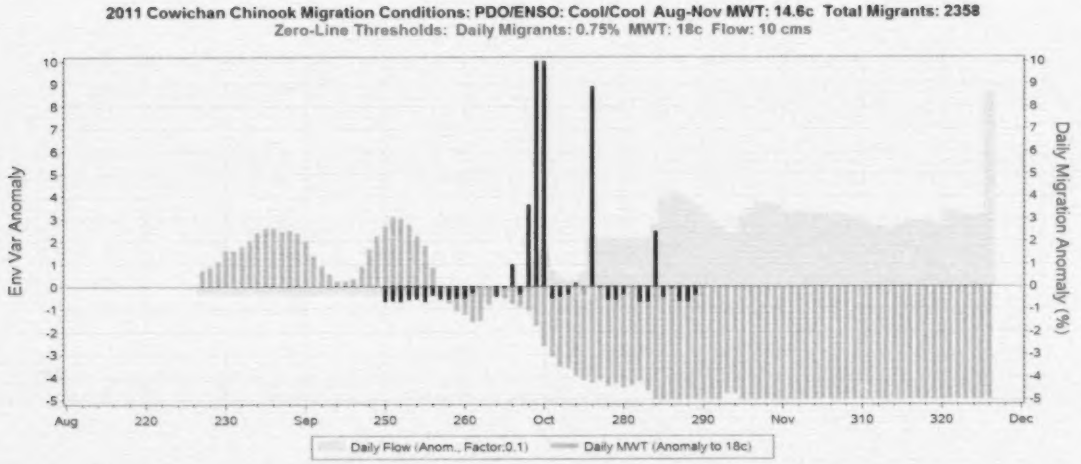

2006 Cowichan Chinook Migration Conditions: PDO/ENSO: Cool/Neutral Aug-Nov MWT: 15.0c Total Migrants: 179
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms
Env Var Anomaly
Daily Migration Anomaly (%)
Aug
Sep
Oct
Nov
Dec
Daily Flow (Anom., Factor:0.1)
Daily MWT (Anomaly to 18c)

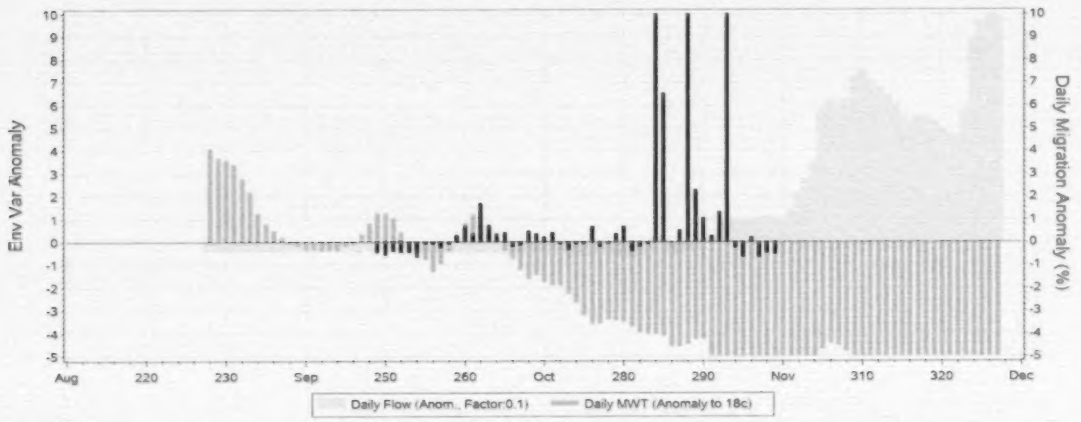

2007 Cowichan Chinook Migration Conditions: PDO/ENSO: Cool/Warm Aug-Nov MWT: 14.2c Total Migrants: 350
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms
Env Var Anomaly
Daily Migration Anomaly (%)
Aug
Sep
Oct
Nov
Dec
Daily Flow (Anom., Factor:0.1)
Daily MWT (Anomaly to 18c)

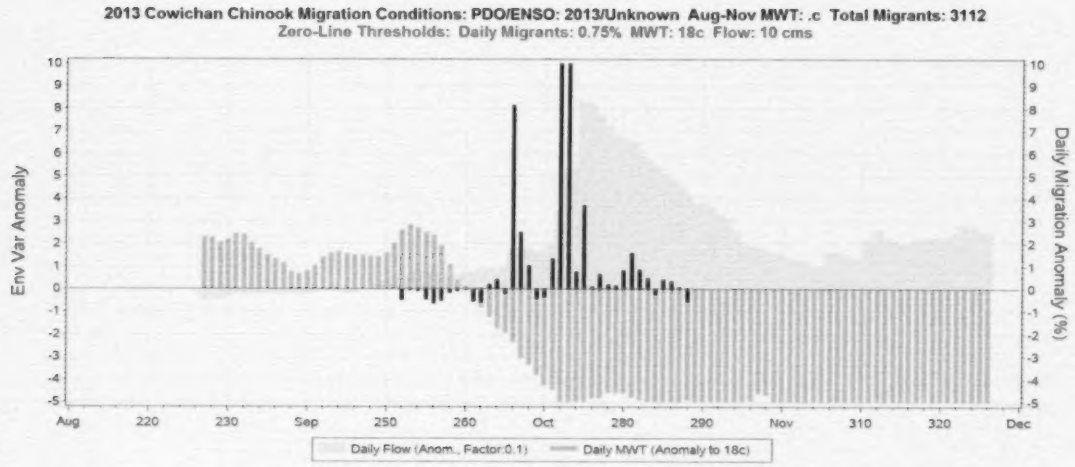

2008 Cowichan Chinook Migration Conditions: PDO/ENSO: Cool/Cool Aug-Nov MWT: 14.6c Total Migrants: 1003
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms
Env Var Anomaly
Daily Migration Anomaly (%)
Aug
Sep
Oct
Nov
Dec
Daily Flow (Anom., Factor:0.1)
Daily MWT (Anomaly to 18c)


2009 Cowichan Chinook Migration Conditions: PDO/ENSO: Cool/Neutral Aug-Nov MWT: 14.6c Total Migrants: 173
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms
Env Var Anomaly
Daily Migration Anomaly (%)
Aug
Sep
Oct
Nov
Dec
Daily Flow (Anom., Factor:0.1)
Daily MWT (Anomaly to 18c)

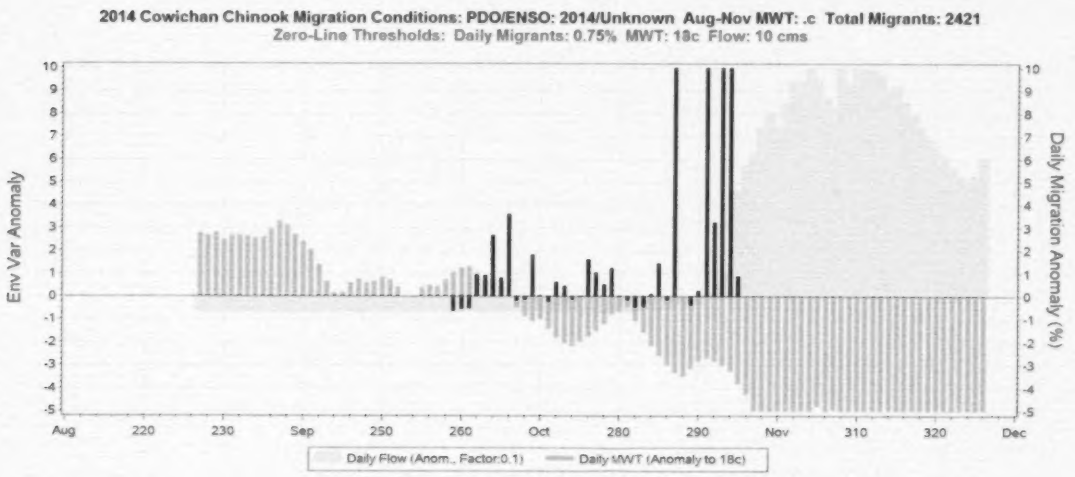

2010 Cowichan Chinook Migration Conditions: PDO/ENSO: Warm/Warm Aug-Nov MWT: 14.5c Total Migrants: 1429
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms
Env Var Anomaly
Daily Migration Anomaly (%)
Aug
Sep
Oct
Nov
Dec
Daily Flow (Anom., Factor:0.1)
Daily MWT (Anomaly to 18c)


2011 Cowichan Chinook Migration Conditions: PDO/ENSO: Cool/Cool Aug-Nov MWT: 14.6c Total Migrants: 2358
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms
Env Var Anomaly
Daily Migration Anomaly (%)
Aug
Sep
Oct
Nov
Dec
Daily Flow (Anom., Factor:0.1)
Daily MWT (Anomaly to 18c)


2012 Cowichan Chinook Migration Conditions: PDO/ENSO: Cool/Cool Aug-Nov MWT: 14.9c Total Migrants: 1559
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms
Env Var Anomaly
Daily Migration Anomaly (%)
Aug
Sep
Oct
Nov
Dec
Daily Flow (Anom., Factor:0.1)
Daily MWT (Anomaly to 18c)


2013 Cowichan Chinook Migration Conditions: PDO/ENSO: 2013/Unknown Aug-Nov MWT: .c Total Migrants: 3112
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms
Env Var Anomaly
Daily Migration Anomaly (%)
Aug
Sep
Oct
Nov
Dec
Daily Flow (Anom., Factor:0.1)
Daily MWT (Anomaly to 18c)

Note: Chinook counts after September 29th were not reliable due to high flows and turbidity, and were excluded from analyses.


2014 Cowichan Chinook Migration Conditions: PDO/ENSO: 2014/Unknown Aug-Nov MWT: .c Total Migrants: 2421
Zero-Line Thresholds: Daily Migrants: 0.75% MWT: 18c Flow: 10 cms
Env Var Anomaly
Daily Migration Anomaly (%)
Aug
Sep
Oct
Nov
Dec
Daily Flow (Anom., Factor:0.1)
Daily MWT (Anomaly to 18c)